Forest impacts on freshwater acidification: an investigation of policy and practice in Galloway, S.W. Scotland

Dunford, Robert

Forest Impacts on Freshwater Acidification: An investigation of Policy and Practice in Galloway, S.W. Scotland

Robert Dunford
University of Durham

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Signed:

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Date:

Abstract

This thesis takes an interdisciplinary approach to investigate factors that influence the extent to which environmental policy and practice are founded on the best available knowledge of the environment. The study focuses on the "forest effect", a long-contested environmental impact whereby afforestation is seen to exacerbate freshwater acidification. A social constructivist approach is taken to focus on the factors that impact the inclusion and exclusion of different forms of knowledge (scientific and lay, local and outside knowledges) held by different environmental actors within the environmental decision making process.

The methodology follows a stakeholder-based approach. It works alongside a group including policy makers, land managers, environmental regulators and NGO "interested parties" to develop an understanding of the contested nature of the "forest effect". Many methods from the social sciences such as participant observation, semi-structured interviews and discussion of participatory maps are utilised. Key differences in the ways that stakeholders conceptualise the "forest effect" are identified. These differences in conceptualisation are identified as being the primary factors contributing to the prevention of information from local knowledge being included within the decision making process. Two significantly different conceptions of the "forest effect" were identified. The first, the "mechanism-down" effect, draws on scientific understandings of the sulphate-scavenging role of forestry and is reflected in policy by a risk-based approach using catchment-based Critical Loads analysis. The second view of a wider "forest effect" was drawn from local knowledge of unusually high acidity and damage to fish populations in afforested areas.

To explore these two "forest effects" in a statistical manner, regional datasets were collated in a catchment-based database that included contemporary and long-term regional field surveys of water quality data, forest maps generated from satellite imagery. Statistical analysis supports a wider "forest effect" than that represented by the "mechanism-down" effect represented in the Forestry Commission's Forest and Water Guidelines. A statistically significant "forest effect" of decreasing pH, charge balance ANC and increasing sulphate, chloride, sodium, Cl:Na ratio and DOC with increasing catchment forest in areas outside of those identified as at risk by the Forest and Water Guidelines. Furthermore, further supporting evidence for a "forest effect" as a factor reducing the potential for long-term recovery from acidification is identified.

Three factors are identified as having influenced the extent to which knowledge of this wider "forest effect" is recognised by environmental policy and practice. Firstly, it was shown that privilege was given by policy makers to one interpretation of science surrounding the "forest effect". The faith put in the science-derived risk-based approaches as sufficient to control for the "forest effect" lead to the exclusion of local knowledge that contradicted this. Furthermore, this lead to real but pragmatic factors (such as the impracticalities of wide-scale water chemistry survey or the cost of felling large proportions of the forest estate) often being either couched in terms of Science, or not being directly discussed, rather than raised frankly as legitimate issues. Secondly, there was little recognition of the complexity and uncertainty surrounding either the nature of the "forest effect" itself, the scientific process used to study it and the ramifications for the varied actors depending on both the forest and water resources. Finally, it was shown that relationships between organisations played a key role in encouraging/deterring the transmission of knowledge; decisions were shown to be based on Better Available Knowledge when the parties involved integrate knowledge from other actors. Hierarchical and institutional ties, on the other hand, were shown to have the potential to restrict the openness to knowledge transfer.

This thesis suggests a social learning approach is taken. This approach encourages the recognition of environmental problems as resource uncertainties to which there is no one determinable answer that suits all and around which decisions can best be legitimised through consensus between impacted parties, informed by the best available scientific data and with recognition of the wider social, political and economic consequences of any action taken.

Acknowledgements

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Right, enough of all that: let's get on with the thesis.

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Acronyms

AWMN – Acid Waters Monitoring Network

CLAG – Critical Loads Advisory Group

CLRTAP – Convention on the Long-Range Transport of Airborne Pollutants

DOC – Dissolved Organic Carbon

FC – Forestry Commission

FWGS – *Forest and Water Guidelines*

GFT – Galloway Fisheries Trust

NEGTAP – National Expert Group on Transboundary Air Pollution

SEPA – Scottish Environmental Protection Agency

SRPB – Solway River Purification Board

SWAP – Surface Water Acidification Program

UN-ECE – United Nations Economic Commission for Europe

WFD – *Water Framework Directive*

Glossary

Acidification: In this thesis "acidification" and "freshwater acidification" are used interchangeably; any other forms of more general acidification are specified and no mechanism by which the acidification has taken place is implied.

Recovery: Similarly, "recovery" is used to mean "the recovery of freshwaters from the impacts of freshwater acidification"; again, no mechanism for this implied.

"Forest effect": Defined as whatever mechanism leads forestry to have an impact on water quality. The understanding of the "forest effect" may vary depending on the person and time, but the "forest effect" itself is explainable, even if we don't know how to yet.

Wider "forest effect": "Forest effect" outside of the areas targeted as at risk by the *Forest and Water Guidelines*

Forest structure data: In contrast to traditional *forest cover* and *forest age* variables *forest structure* data are related to quantifiable physical aspects of forestry such as tree height.

Expert Knowledge: Used in this thesis to describe knowledge collected through empirical scientific methods. The term "expert" refers to the fact that not all individuals have access to this form of knowledge, and is not intended to imply that the knowledge is of itself intrinsically *better* than any other form of knowledge.

Lay Knowledge: The opposite of "expert" knowledge, used in this thesis to define knowledge not attained through the scientific empirical method of data collection but developed organically from an unquantifiable relationship with the subject matter.

Local knowledge: Used in this thesis to mean knowledge derived from an understanding of the local area; in this thesis it is not necessarily "lay" knowledge with which it is often allied in the literature. It is the opposite is "*outside knowledge*" derived from a top-down understanding of the wider issues rather than a bottom-up understanding of local specifics.

Interested Parties: Following the Water Framework Directive "interested parties" is used to cover all bodies who, given the opportunity, might show an interest in how the water environment is managed.

Water quality data: Used in this thesis as a term seen as inclusive of both water chemistry and ecological data.

Chapter 1 : Research Context

1.1 The complexities of Environmental Management

"Compartmentalised science, no matter how erudite, is an insufficient base for knowing enough to anticipate or mitigate the impacts of such complex systems [as the environment]; integrated and synthesised knowledge which pools wisdom from many natural and social sciences is a necessary condition for being Homo sapiens, the "wise ones". *But just knowing enough is not of itself sufficient: acting wisely, and in good time, is also necessary... Sound public policy-making on issues involving science therefore requires more than good science: ethical as well as economic choices are at stake. Such matters concern not only the experts and the politicians but all of us."*

Domingo Jiminez Beltrán: Executive Director of the European Environment Agency (Beltrán, 2002)

1.1.1 Introduction

Environmental management is increasingly the focus of debate. Environmental threats are more commonly being brought to the attention of the general public, and environmental legislation is expanding at both national and international scales as government agencies respond to the demands placed on them. Decision making is complicated by the fact that the environment is a "common pool" resource (Ison *et al.*, 2007) to which numerous stakeholders have varied and contested claims to ownership, access and use as well as different views of its needs and value. Balance between these claims is vital, as often meeting the needs of one party necessitates a deleterious impact on the requirements of others, impacts that can have effects over wide spatial scales, and unforeseen long-term consequences (Hardin, 1968). How the environment is managed therefore decides not only whose needs are met, and whose are not, but also the way in which the environment itself is affected.

As environmental issues are increasingly legitimised as threats, 'objective' and 'impartial' Science is increasingly turned to as a means of mediating disputes. At the same time critical scrutiny of the privileged position of Science as the sole "way of knowing" to be included in the policy-making process is on the rise. Social scientists argue that science itself is socially constructed and that by solely depending on it, alternative forms of equally valid local knowledge are excluded from the decision-making process, leading to policies that may not reflect the understandings of the environment of people who live and work within it.

Policy makers, who need the support of the populus to legitimise their policies, offer consultation as a means to include local concerns; but are left with a need to find a balance that includes widest democratic process and best expert knowledge whilst all the while meeting the varied economic, cultural and political factors that drive the institution within which they are situated.

For local bodies responsible for implementing policy, the policy itself is just one of many pressures that influence how policy is put into practice. In addition to being embedded in the economic, cultural and political context of their institution, they are members of local stakeholder networks which may include parties whose views draw on knowledge other than that reflected in the policy. As a result a balance is needed between local network pressures and their responsibilities under the policy.

Ultimately, any decision making, whether it be for policy or practice, needs to be defensible, and as a result should be based on ***best available knowledge*** but what knowledge is that? Who is it best for? Where is it found? And, who is best to ask? To what extent is it even possible to achieve?

In recognition of the social complexities that surround environmental issues the UK Natural Environment Research Council (NERC) and Economic and Social Research Councils (ESRC) fund joint studentships to address questions such as these in a manner that is "*genuinely interdisciplinary*" (NERC/ESRC, 2008). This thesis is one such ESRC/NERC funded project. It takes a holistic approach with the overarching aim ***to investigate factors that influence the extent to which policy and practice are founded on the*** **best available knowledge** ***of the environment.***

To approach this aim, the thesis focuses on the relationships between policy makers, land managers, environmental regulators and independent "interested parties" as they compete to have their views of the environment represented in policy and supported by practice. Particular attention is paid to the roles of knowledge and power as stakeholders with varied claims over the environment compete to have their understanding of the environment realised in practice.

The long-standing contentious issue of *the impacts of forestry on freshwater acidification*, the so-called "forest effect", is used as a focus for this investigation. The approach taken is grounded in a stakeholder-based methodology that works alongside key stakeholders from the beginning. The following research questions are addressed:

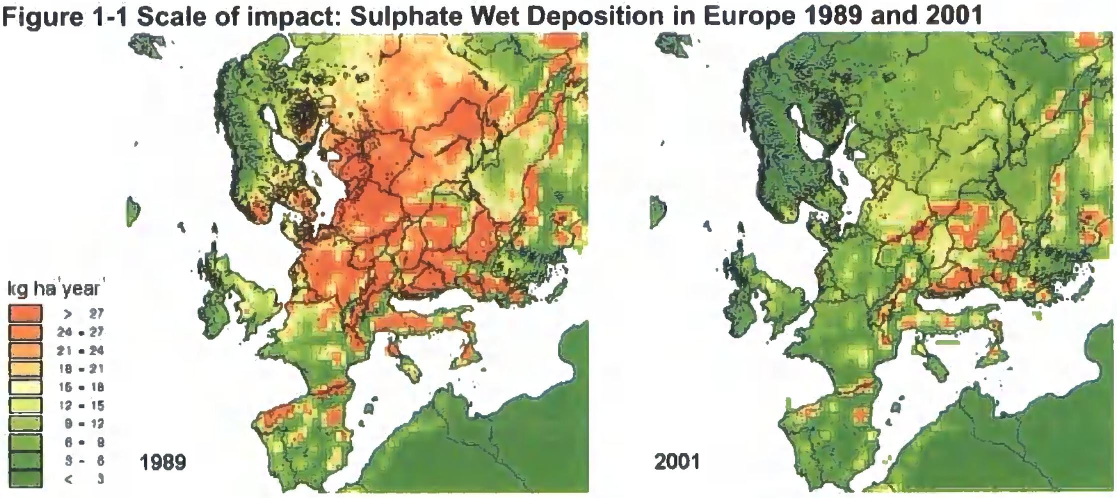
- What is Best Available Knowledge of the "forest effect"?
- What different understandings of the environmental risk ("forest effect") are there?
- What knowledge base is used to support these understandings of risk?
- Which knowledge bases are best supported by evidence provided through scientific methods?
- What factors affect the extent to which environmental management approaches draw on the best available knowledge of the environmental issue in question?
- Which knowledge bases are reflected in policy?
- Which knowledge bases are reflected in practice?

1.2 The Research Context

1.2.1 Freshwater Acidification: over 30 years of concern

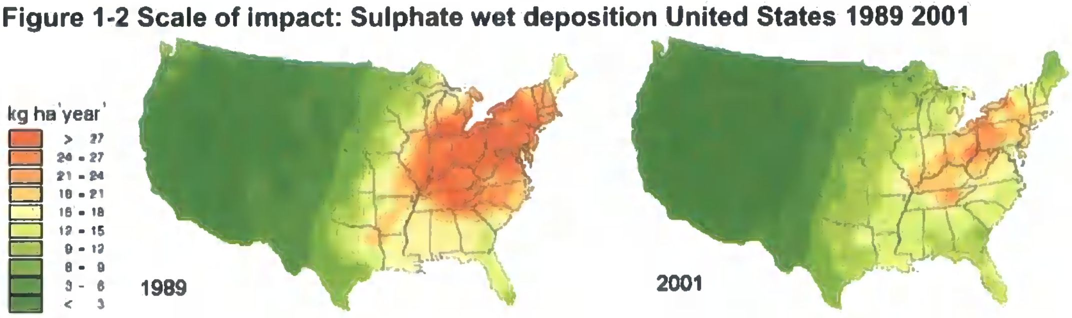
1.2.1a An international issue

Figure 1-1 Scale of impact: Sulphate Wet Deposition in Europe 1989 and 2001



Modified from Brandt and Christensen, 2004 in Milieu ltd. *et al.*, 2004

Figure 1-2 Scale of impact: Sulphate wet deposition United States 1989 2001



Modified from NTN, 2004 in Milieu ltd. *et al.*, 2004
NB maps are of wet deposition and therefore *potential impact* not *damage to freshwaters*

Atmospheric pollution, 'acid rain' and ***freshwater acidification***[1] have been recognised as amongst the most significant international environmental threats to freshwater

[1] In this thesis references to "*acidification*" are always with regard to "*freshwater acidification*"; no reference is made to any other forms.

ecosystems for the past 40 years. Large areas of both Europe (Figure 1-1; Oden, 1968; Henriksen, 1979; Evans *et al.*, 2001) and North America (Figure 1-2; Beamish and Harvey, 1972; Beamish, 1974; Stoddart *et al.*, 1999) have been adversely affected with damage reported to a wide range of terrestrial and freshwater ecosystems as well as the built environment, as have other oil and coal burning nations such as Russia and China.

Freshwater acidification arises when acidic (anion) inputs to a freshwater are greater than that water body's natural buffering capacity (base cations). In these circumstances the water body acidifies, i.e. becomes more acidic, with a lower pH. It is important at this stage to stress the distinction between an *acidic* system, where the pH is *low*, below pH 6 or 7; an *acid sensitive* system, where the buffering capacity of the river or lake is low, so that a small acid input may lead to a rapid change in acidity; and an acidified system, where the pH *has decreased* as a result of acid anion inputs. The major source of acid inputs is *atmospheric pollution* in the form of sulphur and nitrogen compounds output from industrial, transport and agricultural sectors. These pollutants are then transferred to the terrestrial and aquatic environment by three mechanisms: 'dry' deposition, direct transferral between the atmosphere and the surface in contact with it; 'wet' deposition, or "*acid rain*", where the pollutants are transmitted after their solution in rainfall; and 'occult' deposition of pollutants dissolved in cloud droplets. Of these methods 'dry' and 'occult' pollution are greatly increased by the roughness of the surface over which the atmospheric pollutants are passing; this makes rougher surfaces, such as forests, more prone to acid deposition.

If the environmental system receiving the total of these acid inputs is *acid sensitive* these additional acid anions may be sufficient to overcome the natural buffering present and lead to a rapid increase in acidity (decrease in pH), with additional impacts on the ecological systems adapted to that environment. These ecological impacts include, but are far from restricted to, the loss of salmonid stocks in lakes and rivers in Scandinavia (Odén, 1968; Nihlgård, 1970; Jensen and Snekvik, 1972; Almer *et al.*, 1974; Levistad and Muniz, 1976; Henriksen, 1979) North America (Beamish and Harvey, 1972; Beamish, 1974) and the UK (Wright *et al.*, 1980), impacts on other species of life including: bird species, such as dippers (Ormerod and Tyler, 1986, 1990; Buckton *et al.*, 1998; Forestry Commission, 2003a), loons (Parker, 1988), black-throated divers (Eriksson, 1987), ducklings (Desgranges and Hunter, 1987) and grey wagtails (Ormerod and Tyler, 1991); amphibians, such as the common frog (Cummins, 1986; Linnenbach and Gebhardt, 1987), natterjack toad (Beebee *et al.*, 1990), wood frog and spotted salamander (Ling *et al.*, 1986); impacts on mammals, such as otter

(Mason and Macdonald, 1989), mink (Bevanger and Albu, 1986) and other small mammals (Scheuhammer, 1991); as well as forest dieback in acid sensitive regions (Roberts, 1983; Schutt and Cowling, 1985).

The acidification problem has been of such a scale that the United Nations Economic Commission for Europe (UN-ECE) introduced the Convention on the Long-Range Transport of Airborne Pollution (CLRTAP) in 1979 to address the problems of transboundary pollution. It has since been extended with additional protocols that bind signatories to agreeing to reduce emissions of sulphur (Helsinki protocol 1985; Oslo protocol 1994), nitrogen (Sofia protocol 1988) and emissions of volatile organic compounds (Geneva, 1991). The most recent "multiple pollution-multiple effects" protocol (Gothenburg, 1999) aims to reduce Europe's sulphur emissions by at least 63%, NO_x emissions by 41%, VOC emissions by 40% and ammonia emissions by 17% of their 1990 levels.

This review of science and policy is not intended to suggest that the acidification issue was accepted at a political level without debate; the UK particularly was noted for not having signed up to the sulphur protocol (Helsinki, 1985), and was put under significant pressure from Scandinavian countries receiving pollutant output from British power stations to change from being the "Dirty Man of Europe" (see Hajer, 1995a; Battarbee, 2004). These political issues are discussed in more depth in section 3.2.1b. Nonetheless, the UK did (eventually, in 1987) agree to lower its pollution emissions, and succeeded in reducing them in line with the Helsinki protocol, and signed up to the second sulphur protocol (Oslo protocol) and those that have followed; emissions of sulphur and nitrogen in the UK have decreased by 71% and 40% respectively (1986-2001: NEGTAP, 2001; Fowler *et al.*, 2005) and the UK is expected to meet its 2010 targets set by the Gothenburg protocol (1999).

1.2.1b Deposition is on the decrease – so what's the problem?

Despite decreasing sulphate deposition, acidification continues to be a major risk to the health of freshwater environments; whilst there is significant evidence for changes in freshwater sulphate levels in response to emissions reductions (Stoddart *et al.*, 1999; Evans *et al.*, 2001; Davies *et al.*, 2005a; Evans *et al.*, 2008), the improvements in freshwater acidity (increases in pH and alkalinity) are less evident (Evans *et al.*, 2001; Davies *et al.*, 2005a, bb). Furthermore, whilst within a UK context, evidence of ecological recovery exists within Acid Waters Monitoring Network (AWMN) sites "*recovery in most cases is modest and very gradual*" as "*chemical recovery is not yet sufficient to allow further biotic recovery*" (Monteith *et al.*, 2005b).

The lack of rapid recovery has itself become the focus of academic study leading to the identification of potential complicating factors. First amongst these is the fact whilst sulphate deposition has decreased rapidly in response to emissions reductions, the response of nitrogen compounds has been much less dramatic (NEGTAP, 2001; Fowler *et al.*, 2005) leading modellers to suggest that nitrate will overtake sulphate as the major anion at many sites, and that "*in the longer-term nitrate could become the dominant excess anion in most of the UK*" (Curtis *et al.*, 2005). Second, in coastal areas deposition of natural sea salts provide significant inputs of sodium and chloride ions; where more sodium is retained than chloride the additional anion input can lead to significant pulses of acid water which "*appear to be retarding the episodic recovery in many streams*" (Laudon, 2008).

In addition, there are the challenges posed by the uncertainties resulting from the unpredictability of climate change. Changes in "*temperature, precipitation and storminess*" (Wright *et al.*, 2006) which of themselves have complex direct impacts on ecology (Malcolm *et al.*, 2004) will have additional corresponding impacts on the factors mentioned above. Increasing temperatures are likely to increase buffering by increasing base cation weathering rates (Wright *et al.*, 2006). On the other hand, climate change in terms of increased precipitation and 'storminess' could well lead to dilution of buffering conferred by baseflow and more extreme events, increasing the risk to sensitive organisms particularly in areas prone to sea salt deposition (Evans *et al.*, 2008; Wright, 2008). Similarly, changes in Dissolved Organic Carbon (DOC), shown to be increasing in response to acid recovery (Monteith *et al.*, 2007), will play an as yet unquantified role in protecting sensitive fish species by forming complexes with toxic forms of aluminium (McCartney *et al.*, 2003). As a result, the change in focus from a study of acidification to a study of recovery has led to a richer appreciation of the complexity of the issues at hand: emissions reductions may or may not be sufficient of themselves to address all the problems of acidification; further research is needed to identify the role played by all these factors and the extent to which a return to "the way things were" is possible.

... and then there is the "forest effect".

1.2.1c The "forest effect"

The "forest effect", the relationship between forestry and acidification, has been contested since freshwater acidification was first identified. In the late 1970s and early 1980s when the political sphere (certainly in the UK, see Hajer, 1995a; Battarbee, 2004 and Chapter 3 :) had yet to accept the role played by pollutant emissions, forestry was in the running as an alternative *cause* of acidification. Norwegian scientist Rosenqvist (1978) argued that it was land-use change, and not acid deposition that was to blame for the problems identified in the freshwaters. This had particular impact in the UK where, at that time, large areas of the uplands were being rapidly afforested. There was significant debate and pressure was put on the Forestry Commission, responsible for managing the UK's forest reserve, to change its practices. This debate was in part resolved with reference to scientific evidence; Battarbee (1984), using diatom pH reconstructions, showed that acidification had begun prior to afforestation and so the latter could not be the *primary cause* of acidification. There was, however, a clear "forest effect": many other studies had shown that acidification was worse in afforested catchments (Harriman and Morrison, 1982; Stoner and Gee, 1985). A variety of "forest effect" mechanisms were suggested including the drying of soils; the production of acid leaf litter, the uptake of base cations by trees; increase in evaporation; and the altering of water pathways through the soil. The most significant "forest effect" was that forests were particularly effective atmospheric filters, particularly when enclosed in cloud. By "scavenging" airborne anions, they exacerbated acidification of afforested areas (Mayer and Ulrich, 1974; Fowler, 1980; Fowler *et al.*, 1982; Fowler *et al.*, 1989).

As sulphate emissions decline, it is expected that scavenging will decrease, and as a result the "forest effect" now receives much less attention in the academic literature than it did in the 1980s and 1990s (Neal *et al.*, 2004). Neal *et al.* (2004), which included a Forestry Commission spokesperson amongst its authorship, reviewed "the sustainability of UK forestry" and suggested that the reason for this decline in focus is "*perhaps [that] the answers and management choices regarding acidification in forest streams are already clear: until recovery is substantial, widespread or accelerated by liming, the only option is to manage acidified streams to increase production or diversity among acid-sensitive organisms.*" (Neal *et al.*, 2004). They suggest that the approach put forward by the UK Forestry Commission policy response: the *Forest and Water Guidelines* (discussed in much more depth in the chapters to follow) is "positive" in this respect and a means to assure that acidified streams are managed to assist acid-sensitive organisms.

Both academic studies (Helliwell *et al.*, 2001; Harriman *et al.*, 2003) and long-term national monitoring work (Davies *et al.*, 2005a) show that the "forest effect" has not yet been relegated to the past; there is some evidence that fewer sites in afforested areas show signs of pH recovery than moorland sites (Harriman *et al.*, 2003; Davies *et al.*, 2005a). The mechanism for this is unclear; it may be that the enhanced capture of the diminishing air pollutants is enough to tip the balance; alternatively, the impact may be through one of the other processes that were less the focus of attention when air pollution was at its height; or, it could be just that forest practices make the statistical detection of trends difficult (Davies *et al.*, 2005a); "further monitoring" is required to determine this.

What is clear, is that fisheries interests within the areas impacted by acidification have suffered for at least 30 years as a result of the combined effects of forestry and acid deposition, and that these stakeholders do not necessarily see national policies as meeting their needs, or recognising their knowledge; in fact, they do not necessarily even see the policies as addressing the right issues having targeted emissions rather than forestry itself:

"*If you look at the decline in salmon fisheries in the Fleet it began in the 1970s; the Cree was slightly later, lost its salmon populations in the 1980s – all this is exactly when the planting was done – this is when the fish started to diminish – particularly in areas which had been planted ... Emissions were at their highest in the 1960s, and also salmon stocks had never been higher. Now how do you relate that? Since the 1960s emissions have been falling but it's only in the last year or two that we have seen any improvement in the rivers.*" (Local Fisheries Stakeholder, 2005)

The "forest effect", argued to be under control by Neal *et al.* (2004), is clearly alive and well in the eyes of certain stakeholders local to the impacted regions. How do these stakeholders come to these conclusions? What knowledge do they draw on? Is this knowledge valid? Who decides this? Have the local stakeholders misunderstood the science? Or has the science misunderstood the problem? Or is it a bit of both?

Whatever the case, it is clear that the story of the "forest effect" is not quite as *agreed* as the policy makers suggest. This thesis takes a holistic approach that uses a stakeholder-based methodology in one of the most acidified regions in the UK to investigate the factors that affect the extent to which forestry policy and practice address the issues of freshwater acidification.

1.3 The Complexities of Integrated Catchment Management

1.3.1 Acidification and Water Policy

The existence of large areas of forestry within catchments is recognised to have had very real consequences for the water quality in acid-sensitive waters (Harriman and

Morrison, 1981; Stoner *et al.*, 1984; Stoner and Gee, 1985; Harriman *et al.*, 1987). However, whilst CLRTAP was introduced to reduce emissions, the land-use contribution to acidity, including forestry and the "forest effect", have until recently been left under the remit of national environmental legislation where they provide significant challenges to land managers and environmental regulators alike. The reason for this is that as a diffuse source of pollution acidification cannot be tied to a single location and addressed with simple countermeasures. Instead, to avoid forestry worsening conditions in acid sensitive areas, catchment scale planning is required to ensure that areas planted with forestry have sufficient base cation buffering that the added acid input it contributes has no effect.

Until recently, problems such as these have not been the focus of either national or international water/environment policy. These policies have tended instead to focus on point sources of pollution (e.g. the UK's Control of Pollution Act (1974) and its amendments[2]) and tended to shy away from the considerable challenges required to minimise diffuse pollution at a national scale[3]. However, the introduction of the international target of "sustainable development" from summits and agreements such as the UN Conference on the Environment and Development (Rio de Janeiro, 1992) have meant that governments, and particularly their land-use/ environment sectors, are increasingly recognising the need to identify ways to balance environmental health with economic growth.

In Europe, the Water Framework Directive (WFD; 2000/60/EC) represents one of the most ambitious policies attempting to approach the issue of sustainable development. By putting a drive to "good *ecological* status" at the heart of legislation the WFD dramatically shifts the focus of water regulation away from the point-source focus of previous policies; for European Member States any impact that affects ecological health needs addressing: diffuse pollution impacts such as forestry and acidification are now very real risks of failure to comply with European law[4]. Under the EU Water Framework Directive, policy is now necessitating Member States to "*identify the individual river basins within their national territory*" and to "*assign them to individual River Basin Districts (RBDs)*" (WFD, Article 3) for which "*Member states shall ensure that a River Basin Management Plan (RBMP) is produced*" (WFD, Article 13) thus

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[2] Control of pollution act as modified by the Water Act (1989) in England and Wales and the Water Resources Act (1991) in Scotland

[3] Exceptions regarding specific pollutants and specific target areas exist; c.f. Nitrate Sensitive Areas designated under the Water Act (1989) and Nitrate Vulnerable Zones designated by the Nitrates in Water directive (91/676 EC).

[4] Similar processes are under way in North America, where the Clean Water Act also includes "*watershed planning and management for the control of pollution*" (Novotny, V., 1999. Integrating Diffuse/Nonpoint pollution control and water body restoration into watershed management. *Journal of the Institution of American Water Resources Association*, 35(4): 717-727.) that introducing similar drives to tackle diffuse pollution.

recognising the need to manage the common water resource as an integrated environmental system. In addition the WFD recognises the complexities that arise from multiple stakeholders and stresses that policy implementers must "*encourage the active involvement of all 'interested parties*" (WFD, Article 14).

For environmental management to address the complex issues raised by legislative drives such as the WFD focus has been placed on the need for "Integrated Catchment Management" concerned with "*balanced, equitable and sustainable management of water, land and other natural resources*" (Watson *et al.*, 2007). The notion of "integrated water management" is not new; the concept has seen much use as a means to tackle individual problem areas (such as nitrate vulnerable zones) but its widespread application at a national scale is far less common (Cf. Australia's Landcare approach; Landcare, 2003) and rare at an international scale. The reason for this is simple; the environment is very difficult to understand and predict, as are the views and actions of the many stakeholders who depend on it. This makes it difficult for policy makers to make simple rules that work in all situations (Table 1-1).

Table 1-1 The Complexity of integrated catchment management

Common Pool Resources	The water environment is a resource over which issues of ownership, use and value are difficult to decide.
Multiple Stakeholders	Many actors have claims on the water resource in terms of both the impacts they have and the needs they require from it.
Interdependency	The requirements of these actors cannot be addressed in a vacuum; issues of interdependency require the issues to be addressed holistically.
Controversy	There are multiple views over the "best management approach" to resolve any one issue, reflecting the multiple actors involved.
Complexity	Very often the target issue is hard to define, measure and monitor.
Uncertainty	As a result it is often necessary to manage environments in "***situations of scientific uncertainty and sometimes in ignorance about the nature of the future of these resources.***"

Text and themes modified from Blackmore (2007)

Sustainable resource management poses significant challenges even in simple systems, requiring: a) joined-up and integrated thinking; b) good management; c) efficient use of resources; d) good science; and e) social responsibility to be combined to be successful (WWF, 2000). These challenges are particularly significant regarding the water environment, as water is a "common pool" resource over which no one stakeholder has sole claim. The interdependent nature of these claims means that a condition of *subtractability* exists where "*use by one user will subtract benefits from another user's enjoyment of the resource system*" (Ison *et al.*, 2007). It is therefore the decision of catchment managers that determine who has what access to what level of the common pool resource. As a result these managers (both policy makers and practitioners) are faced with "resource dilemmas": situations where no one solution is good for all. As a result, the solutions made must be demonstrably founded on some robust base and agreed and legitimised by all users of the resource: but how is this to be achieved?

The traditional answer to this question has been with reference to "Science[5]"; the established methodologies put forward by the natural sciences. Monitoring programs are put in place to quantify the risk to the environment, and mechanisms are determined to explain these risks and generate models to estimate the risks beyond current knowledge. By following recognised scientific methods based on repeatable observation under controlled conditions, the results are seen to be scientifically objective and politically neutral and can therefore be a perfect means to mediate in disputes between the various actors with demands on the water environment.

1.3.2 A Social Constructivist Critique

More recently, however, social theorists (e.g.Beck, 1992; Hajer, 1995a; Wynne, 1992) drawing on the work of Kant, Kuhn and Foucault have critiqued the position of 'Science' as the privileged tool for policy making. They criticise the *realist* conceptualisation of Science as 'objective', 'apolitical' and 'certain', and, drawing on the philosophy of *social constructivism,* stress the role of social forces in the "creation" of Science and the acceptance of "facts". They argue that by following a *realist* perspective, the role of Science as a tool of power that is always *done* by someone *for* some purpose is overlooked. They argue that by privileging this "way of knowing" over others, local and lay knowledges from outside official governmental institutions are inhibited in terms of their ability to contribute to policy formation: "*institutionalised rationality of scientists and experts has become a source of problems itself*" (Beck, 1992).

A recognition of the power relationships inherent in the process of knowing leads to a necessary recognition that it is impossible to "know" a catchment *objectively*; any one interpretation of the water environment will necessarily reflect the views of the interpreter. With such a large number of stakeholders who draw on different types of knowledge to different extents it "*is no longer possible to rely **only** on scientific knowledge for management and policy prescriptions*" (Ison *et al.*, 2007). The significance of this perspective is considerable: how are decisions to be made if there are multiple ways of knowing?

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[5] "Science" with a capital "S" is used to refer to the traditional realist natural science ontological, epistemological and methodological approach to knowing the environment based on an empirical scientific method of fact and theory generation from repeated observation. See Table 2-1

An approach to management that takes this social approach to uncertainty into consideration is that of *Social Learning* (e.g.Ison *et al.*, 2007; Blackmore, 2007). This approach is based on a theoretical framework that uses *social constructivism* rather than *scientific realism* as its theoretical framework:

"*Social Learning is based on the idea that the sustainable and regenerated water catchments are the emergent property of social processes and not the technical property of an ecosystem. That is, desirable water catchment properties arise out of interaction among multiple, interdependent stakeholders in the water catchment.*" (Ison et al. 2007)

"*It presumes that neither the ends nor the means of social interventions can be fully known in advance, and that understanding and consensus on them must be built up through practical experience. Mistakes are unavoidable but with ongoing evaluation, results can be improved.*" (Blackmore, 2007)

The focus on incorporating the knowledges of multiple stakeholders is key to the Social Learning approach: *consensus* functions as an alternative to *scientific proof* for the base on which the legitimacy of a management approach is founded. This thesis draws on the ideas of social learning to define "Best Available Knowledge" as: ***the theoretical holistic state of knowledge which results from the evaluation of multiple stakeholders' knowledges (whether expert, scientific, lay or local), and the best available scientific data regarding the issue.***

The Social Learning approach is relatively new, and is rarely seen integrated into national policy approaches (Cf. Landcare, 2003); Beck (1999) comments that there is an increased "*awareness of our unawareness*" accompanied by changing attitudes towards increased public participation, such as the WFD's encouragement of the "*active involvement of all 'interested parties'*", reflecting an increasing "*democratisation of knowledge*" (Hajer, 2003). As a result policy makers find themselves having "*to rethink the way in which uncertainties are dealt with socially*" (Hajer, 2003).

In reflection on this, Hajer argues that we now need to consider the policy process as that of "*knowledge deliberation*" where the multiple stakeholders with competing knowledges are involved in a "*credibility struggle*" (Epstein, 1996 in Hajer, 2003) in which "*facts and research projects are 'enlisted' to back up particular problem solving strategies*" (Hajer, 2003). This raises the key questions for this thesis: ***what understandings of environmental risk are there? What knowledge bases are used to*** *support these understandings? And what factors affect whose knowledge is included in policy and practice?*

Ultimately, the answers to these questions rest on the shoulders of policy makers and land managers: this study focuses on the *knowledge deliberation* over the "forest effect" in order to determine *what factors affect the way the environment is managed to address the problem of acidification? And to what extent does this approach match with best available knowledge?*

1.4 Thesis Overview

1.4.1a Summary

The research context of this thesis is in summary:

- Freshwater acidification has been a complex real issue with significant long-term consequences for catchments.
- The "forest effect" as a land-use exacerbation of acidification has a long and contested history and is still believed by some to be playing a role, hampering the recovery of afforested catchments.
- The focus of national and international legislation is only now beginning to address diffuse pollution (such as acidification); to do so integrated catchment management is necessary
- The common pool nature of the water environment makes catchment management difficult; both the number of stakeholders and the uncertainty of the environment make decision making complex
- Social constructivism indicates that Scientific knowledge, traditionally privileged in decision making, is neither objective, impartial nor certain enough to be relied upon as the sole source of knowledge for decision making.
- Lay/Local knowledge is equally legitimate and must also be included in the decision making process.
- Stakeholder participation is becoming increasingly commonplace providing the potential for local knowledge to be involved in the decision making process.
- The extent to which the knowledges of any individual actors are reflected in policy and practice ultimately rests in the decisions made by policy makers and land managers.

1.4.1b Aims and Research Questions

The overarching aim of this thesis is to ***investigate factors that influence the extent to which policy and practice are founded on the* Best Available Knowledge *of the environment*** using a case study of the "forest effect" on the acidification of freshwaters.

Drawing on a social learning approach to decision making in consideration of the implications of the *social constructivist* arguments regarding the partiality of Scientific knowledge and the importance of local knowledge 'Best Available Knowledge' has been defined as follows: *the theoretical holistic state of knowledge which results from the evaluation of multiple stakeholders' knowledges (whether expert scientific, lay or local), and the best available scientific data regarding the issue.*

With this in mind this thesis tackles three overarching research questions:

- What is the Best Available Knowledge about the "forest effect"?
- What factors influence the extent to which Best Available Knowledge of the "forest effect" is incorporated in *forestry policy*?
- What factors influence the extent to which Best Available Knowledge of the "forest effect" is incorporated in *forestry practice*?

1.4.1c Methodological Challenges

One of the greatest challenges for a study such as this, where an understanding of both social and natural sciences is required, is in determining a methodology which enables the two approaches to be combined. In order to achieve this, in a fashion that is genuinely interdisciplinary, the following methodological steps were taken:

- A group of key "stakeholders" including policy makers, forest managers, environmental regulators and representatives of "interested parties" was identified in Galloway Forest District, one of the most significantly acid-impacted areas in the UK.
- Social-science methodologies were used to develop a long-term (c.1978-2006) holistic understanding of the different stakeholder understandings of the "forest effect" and the knowledge they have drawn on to reach these.
- This stakeholder-based understanding was used to determine the extent to which forestry policy and practice are seen to have addressed the "forest effect" as it is understood by the stakeholders, as well as the factors that have influenced this.

- Methodologies from the natural sciences were applied to collect, analyse and map an understanding of the "forest effect" founded on best available science.
- Interdisciplinary methodologies were used to present and explore maps of stakeholder knowledge/data in a stakeholder discussion meeting.
- Conclusions were drawn that combined the results from all approaches to allow management recommendations to be suggested.

1.4.1d Thesis Structure

The following chapter (Chapter 2) introduces the project methodology in more detail. The remaining chapters address to different extents the relationships between science and local knowledge, policy and practice to tell the story of the relationship between stakeholders, science and the "forest effect" in Galloway, South West Scotland.

Chapter 3 discusses the Forestry Commission's views of the *Forest and Water Guidelines* which include their policy response to the "forest effect". The changing relationships between policy making, institutional forces and scientific knowledge between the identification of the acid rain issue and the most recent edition of the Guidelines (c.1978-2003) are discussed in terms of the impacts of the policy decisions on Galloway in practice.

Chapter 4 focuses on the views of local stakeholders regarding current forestry policy (Forestry Commission, 2004) and the "forest effect" it represents. Differences between knowledges of the "forest effect" are discussed with reference to the academic literature.

Chapter 5 explores the role of inter-stakeholder relationships in Galloway from 1978-2005 in determining the extent to which the knowledge held by the different stakeholder organisations is realised in policy and practice.

Chapter 6 outlines the methodology by which a regional spatial database of available catchment and water quality datasets can be combined to provide data products for the remainder of the thesis.

Chapter 7 explores the role of "best available knowledge" with stakeholders by presenting the results of a stakeholder meeting at which maps representing individual stakeholder views of the environment are discussed.

Chapter 8 identifies the extent to which the "forest effect" identified by local stakeholders is reflected by a scientific analysis of the "best available data".

Chapter 9 attempts to identify whether a "forest effect" on freshwater recovery can be identified by a scientific analysis of the "best available data".

Chapter 10 synthesises the findings in the thesis to provide management recommendations regarding of the "forest effect".

Chapter 11 concludes the thesis.

Chapter 2 : Theory and Methods: A stakeholder-based approach

2.1 Introduction

As indicated in the previous chapter, the aim of this thesis is to ***investigate factors that influence the extent to which policy and practice are founded on the* Best Available Knowledge *of the environment*** using a case study of the "forest effect" on the acidification of freshwaters in Galloway, South West Scotland. This chapter introduces the theoretical framework and methodological approach taken by this study.

2.2 Theoretical Framework

2.2.1 Social Constructivist Considerations

This thesis is founded on the belief that Best Available Knowledge for environmental decision making can be approached by an evaluation of the knowledge held by multiple stakeholders, and the best available science. The acceptance that multiple stakeholder knowledges exist, and take different forms (such as "expert", "lay" or "local"), draws on arguments put forward by *social constructivism* as a counterpoint to the traditional *realist* natural science approach to understanding the environment. Before introducing functional details of the study area and the methodological approach adopted, it is important to understand the theoretical context in which the research was performed, starting with a consideration of the impacts of *constructivist* and *realist* conceptualisations of the environment.

A note on terminology:

In the following chapters the term "*Knowledge*" is used following social theorists in a fluid way that accepts that there are many *Knowledges* and *"Ways of Knowing"* that combine different *ontological* (questions of being/existence: is there an environment that we can know?), *epistemological* (questions of knowing: in what way(s) is it possible to know the environment, in theory) and *methodological* (questions of doing: in what way(s) is it possible to know the environment, in practice) approaches to knowledge and knowledge acquisition (Moses and Knutsen, 2007).

Table 2-1 Comparing theoretical frameworks

	Realist-Naturalist	*Constructivist*
ONTOLOGY	**(Questions of being)**	
Is there a: "Real World"?	Yes; whether or not humans are there to observe it.	It's not that simple: the "real world" doesn't exist outside of our construction of it through the senses. As such it is constructed differently by different observers and contextual settings.
Are there: "Facts"?	Yes; there are independent particulars that we can observe with our senses. It is possible to differentiate between value-laden and factual statements.	In natural science "facts" only become "facts" when agreed as such through social processes. Humans do not have fixed and permanent attributes independent of their context, they are adaptable and malleable: naturalism is an unsatisfactory basis for social science.
Is there: "Truth"?	Yes; a statement is true if it corresponds to the state of affairs in the real world.	Truth is subjective; it is important to consider the relationships that link the mind and world; there are many social worlds: this has significant implications for any claims to a single truth.
EPISTEMOLOGY	**(Questions of knowing)**	
What is: "Knowledge"?	Knowledge is obtained by systematic observation of associated phenomena.	It is possible to obtain knowledge through a variety of means; not just the systematic scientific observation of phenomena. Whatever approach to knowledge used it is necessary to protect, enhance and exploit the context. Knowledge is intersubjective: its importance is in its (dis)agreement between actors.
	By using these observations to falsify hypotheses it is possible to uncover regularities and approach universal laws. If done following rigorous scientific methods the findings are both objective and apolitical.	There are no big theories; the truth isn't just 'out there' it is always situated in a social context. Knowledge is always *for* someone; it provides power and influence The best approach is with scepticism and self-awareness
	By continually refining and testing hypotheses knowledge grows.	Knowledge is context dependant
METHODOLOGY	**(Questions of doing)**	
How do we get at: Knowledge?	By repeatedly observing and recording regularities using the senses.	By studying the repetitions and patterns present in the socially constructed world and identifying them in the light of their contexts that give them meaning.
Blue text: theoretical stance taken in this thesis (see section 2.2.1g) Modified from text and content of Moses and Knutsen, 2007		

2.2.1a Constructivism/Realism

Table 2-1 introduces the major differences between the two extreme[6] approaches to knowing of *realist* natural science and *constructivist* social science. The *realist* stance argues (often implicitly) that there is an independent real world to be known, from which data (or, following Latour and Woolgar (1979); facts) can be collected by empirical measurement. These data are then used to test hypotheses and, by repeatedly falsifying these hypotheses (Popper, 1963), patterns can be identified and general laws refined, thereby expanding knowledge. The methods applicable to attaining this knowledge are those of the natural sciences, based on empirical measurement and controlled conditions. By contrast the *social constructivist* stresses the importance of context. The real world, social constructivists argue, is that interpreted by our senses, and as such is inherently subjective; it cannot be known without reference to both the "knower" and the context in which they "know". This means that a "fact" drawn from it is only a "fact" to the extent that it is agreed to be "truth" by other "knowers".

In terms of determining factors that may influence the ability of environmental management to be based on Best Available Knowledge, this has significant implications. For example, if a pH reading is seen as an objective reflection of acidity, it can easily be used as a decision making tool. However, social constructivists argue that there are more complex dimensions to consider. Some might argue over the ontological existence and socially constructed relevance of a concept such as, for example, pH and that its meaning and value is only granted through social recognition; I take a pragmatic (weak) constructivist stance on this point, and acknowledge these ontological concerns but do not see them as useful as tools for the purposes of answering questions about how the environment is managed. On the other hand, the recognition that an individual pH reading cannot be seen as a "fact" without considering its context and the number of technical, environmental, social and political factors that have led to that "fact"'s creation is of vital importance to this thesis. Latour and Woolgar (1979) illustrate this with reference to "facts" such as a finished figure or datasheet of numbers from a medical research laboratory and stress that:

"*Once a string of operations has been routinised, one can look at the figures obtained and quietly forget that [many diverse scientific disciplines] actually made this figure possible. Once the data sheet has been taken to the office for discussion, one can forget the hundreds of dollars that have gone into its production ... it is easy to forget that the construction of the paper depended on material factors. The bench space will*

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[6] These views are deliberately extremes, see below.

be forgotten and the existence of laboratories will fade from consideration. Instead 'ideas', 'theories' and 'reasons' will take their place. ... Without the material environment of the laboratory none of the objects could be said to exist, and yet the material environment very rarely receives mention. It is [a] paradox which is an essential feature of science." (Latour and Woolgar, 1979)

The argument made by the constructivist approach is that these vitally important factors are "*taken for granted as being merely technical matters*" (Latour and Woolgar, 1979). Uncontrollable environmental effects, pragmatic choices, accidental mistakes and more deliberate human actions all impact on the notions of a repeatable approach unaffected by the social sphere that underlie the realist view of the scientific method. Any claims to a "pure" objective science must therefore be treated with scepticism.

This thesis explores the extent to which pragmatic factors such as these affect the extent to which policy and practice have access to *Best Available Knowledge*.

It should be noted that the construction of a realist natural scientist and a constructivist social scientist at opposing ends of the debate is deliberately polemical. I am not claiming that all natural scientists are naïve to their dual natures as social and political actors nor that many criticisms of the realist approach can be dismissed by the natural scientist as irrelevant to the task at hand or simply obvious statements of how science can be done badly (although I would argue that doing so involves an inherent acceptance of a constructivist stance of a science which is 'done' to be of 'use' to someone). However, as the following sections go on to explain, the power and privilege given to scientific knowledge by social actors, as well as the complexity of environmental issues and the inherent incompleteness of Science, stress the importance of considering the wider social context in environmental decision making.

2.2.1b Knowledge/Power

Furthermore, the constructivists argue, the scientific method can no longer be seen as apolitical. Foucault (1980) argues that power and knowledge are inherently intertwined so that one cannot be seen without the other:

"*The exercise of power itself creates and causes to emerge new objects of knowledge and accumulates new bodies of information ... the exercise of power perpetually creates knowledge, and conversely, knowledge constantly induces effects of power ...It is not possible for power to be exercised without knowledge, it is impossible for knowledge not to engender power.*" (Foucault, 1980)

In an investigation of environmental decision making it is always again necessary to reflect on the context in which knowledge is created – who are data collected by? From where and why? Seemingly objective choices such as locations of monitoring sites may have significant impacts on the knowledge/power claims that can be made about the river upstream and how it should be managed: "*when we classify objects we operate within a system of possibility – and this system both enables us to do certain things and limits us to this system and these things*" (Philip, 1985). As a result, any claims to the political neutrality of science, in defence of its use as a decision making tool should be treated with extreme caution and with much reference to context.

This thesis explores the role of power/knowledge choices as a means of constraining what it is possible to know; and the impacts of these choices on the potential of stakeholders to achieve *Best Available Knowledge*.

2.2.1c Lay/Local knowledge and the privilege of science

As a way of knowing, the empirical hypothesis testing approach taken by *realist* science is not the only way of approaching knowledge. Considerable research has shown that "lay" knowledge: that developed by lived experience rather than empirical testing; and "local" knowledge: that produced within the region in question are often less privileged than "expert" knowledge: that based on science and often generated by institutions and academics "outside" of the local context (see Glossary).

Wynne (1992) demonstrates the relevance and dangers of this inherent privileging of science with reference to a social/environmental case-study of Cumbrian sheep farmers' responses to scientific advice about the restrictions introduced following the 1986 Chernobyl fallout. His work showed that "*the scientific perspective was just as socially grounded, conditional, and value laden as the other*" (Wynne, 1992) as initial advice from scientists over the length of time it would take fallout to pass through the system (3 weeks) was shown to be based on a model designed for the wrong soil type (the pollution was still there 2 years later). Wynne showed that privilege was often given to scientific knowledge by local stakeholders despite contrasting views "*farmers implicitly recognised their social dependency on scientific experts…even if they held dissenting beliefs. As one farmer put it: 'you can't argue with them because you don't know – if a doctor jabs you up the backside to cure your headache you wouldn't argue with him would you?'*". (Wynne, 1992)

Furthermore Wynne demonstrated that local/lay knowledge was not always of lesser value than scientific knowledge with an example that followed scientists as they tested the mineral "bentonite" as a means of absorbing the caesium from the fallout. To test the bentonite's impact scientists penned sheep on comparative plots of bentonite-treated land and zero-bentonite land, with the aim of comparing the health of the two sheep populations. Farmers pointed out that the sheep were used to roaming over the fells, and that they would waste if kept penned up, thus ruining the experiment. Although ignored, the farmers' (lay/local) knowledge was proved to be correct and the experts had to "*quietly abandon*" their experiments (Wynne, 1992).

In this thesis knowledge is seen as socially embedded in stakeholders and it is the interpretation of this knowledge that is of importance: local/lay interpretations are of equal value to interpretations based on scientific knowledge. Furthermore particular attention is paid to the way that one form of knowledge is privileged over another.

It should be noted that the exclusion of local knowledge is not a flaw in the Scientific method *per se* but a problem with the use of science in decision making. The hypothesis testing methodology encourages the falsification of findings; it could be argued that lay knowledge has a role as a means for generation of hypotheses for testing, and this is certainly the case: however, for issues of environmental management this is a) often does not happen (Wynne, 1992) and b) takes too long, and, in conditions of uncertainty may not be able to provide the level of certainty decision makers need. The second of these issues is discussed in the following section.

2.2.1d Certainty and the Precautionary Principle

As demonstrated in the Wynne (1992) case studies Science does not always provide 'the answer'. This is recognised by the scientists themselves; often the environmental system is so complex "*that you by and large have to work on the strength of circumstantial evidence: it is difficult to get absolute proof. It's really about the threshold of circumstantial evidence that you accept*'" (Hajer, 1995a quoting Professor Last of the ITE). Hajer (1995) draws on a case study of the evolution of the acid rain debate in the UK to show that, despite the difficulty of achieving a definitive answer, the need for scientific certainty is used as a means of delaying action in the policy sphere. In the acid rain debate government agencies such as the former Central Electricity Generating Board (CEGB) followed "*a natural science conceptualisation of the problem. Acid rain was framed as a question for research. It had to be established whether there was genuine environmental damage which could be attributed to sulphur* *emissions produced by CEGB power-stations. If this could be proved to be environmentally effective as well as the most cost-effective solution ... [Flue desulphurization equipment] should be installed*".

Opponents of the CEGB view argued that "*simply to plead for more research into cause and effect is but to procrastinate*" (HoC Environment Committee in Hajer, 1995a). These opponents did not object to using science but "*the distinction lay in the kind of scientific evidence that was deemed appropriate and its connections to particular policy actions...[their views were] supported by scientific advice [yet they] argued that research should not be devoted to finding proof but to making an ecological assessment of "risk" involved in action and non-action*" (Hajer, 1995a).

In making this argument the HoC Environment committee evokes the precautionary principle included in the Rio Declaration of 1992 which declares that "*where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation*". The precautionary principle has much significance for environmental decision makers, but its application in practice is complicated by the need to determine the costs and benefits of any environmental (in) action. This in turn raises the question of how to place a value on the environment (Ison *et al.*, 2003) a problem that is "inherently political" and cannot be solved from a scientific standpoint (Gezner, 2008).

In this thesis, the approach taken by stakeholders to uncertain science and their (un)willingness to follow the precautionary principle is a factor that will influence the approaches taken by both policy and practice to the management of the "forest effect", and in turn their approach to *Best Available Knowledge.*

2.2.1e Network Theory

"*What emerges as most deserving for analysis [in the field of the sociology of scientific knowledge] is how particular claims and attributions of expertise come into being and are sustained, and what the implications are for truth and justice; the intellectually gripping problem is not how to demarcate expert from lay knowledge or science from politics... such demarcations will keep being produced in any case, in the everyday work of scientists, citizens and institutions of governance. Showing what is at stake in the making of such boundaries is another matter*" (Jasanoff, 2003).

As the above quotation stresses, recognising the relationships between power and knowledge and the ways that knowledges are privileged, included or excluded is key to understanding decision making. Network Theory is a theoretical approach from the social sciences that, considering this point, provides *"a lens through which any area of policy making and implementation can be viewed"* (Marsh and Rhodes, 1992). A Network Theory approach sets out to investigate the relationships between *"different actors, decisions, institutions and structures and the effects of these relations on policy outcomes"* (Bulkeley, 2000). It focuses on the links between policy actors whose interdependencies on a common resource require them to bargain with one another to secure policy outcomes (Smith, 1997). These networks are conceived to develop as interested parties (including individuals, NGOs and government institutions) gather around the government agency in charge of implementing the policy in the hope of influencing its development in their favour (Bulkeley, 2000).

In terms of this thesis, the approach is particularly valuable as a way to interpret the *knowledge deliberation* (Hajer, 2003) process around catchment management issues (See section 1.3.2) where multiple stakeholders draw on different knowledges to compete for influence over the water environment. The policy network approach regards the knowledge deliberation process as neither *"open to the participation from all interested parties, [nor] restricted to the privileged few ... [However,] within any particular network, variations in power, resources, and access mean that certain groups are excluded while others maintain a privileged position"* (Bulkeley, 2000).

The factors that influence the inclusion and exclusion of different actors and the knowledge that they have to offer are of prime importance to this thesis. The Network Theory approach conceptualises government institutions as actors in a continually evolving policy network. By institutionalising one particular knowledge in policy, one interpretation of the environment is privileged over others in terms of its influence on practice. The strength of the relationships between other actors in the policy network and the institution responsible for implementing policy are therefore key factors that facilitate and impede the access of the implementing institution to other knowledges.

The policy network approach is not just a tool for the *"description of interest-group interactions, but also a means of analysing policy processes and outcomes."* (Bulkeley, 2000). As the relationships between network members are in *"a continuing process of re-negotiation"* (Marsh and Rhodes, 1992), it is possible to identify the means by which individual actors engage in "coalition building" with other members of the network in order to reach consensus and influence management change.

Bulkeley (2000) reviews two different types of coalition: the "advocacy coalition" of organisations grouped around core beliefs determined to have their claims accepted and acted upon (as seen in Jenkins-Smith and Sabatier, 1993; Sabatier, 1998); and, the "discourse[7] coalition" of stakeholders who, though not necessarily sharing the same beliefs utilise the same "storylines" to describe the issue and motivate action (Hajer, 1995; Bulkeley, 2000).

In the "advocacy coalition" framework, "*coalitions seek to turn their beliefs into policies by 'out learning' their adversaries ... to keep abreast of events and in tune with changes of the subsystem*" (Jordan and Greenaway, 1998). This ongoing competition is not, however, usually enough to lead to policy change; instead "*changes in core aspects of policy require an exogenous shock [from] outside the system*". Drawing on a review of British water pollution policy 1955-1995 Jordan and Greenaway (1998) illustrate that despite increased understandings of the water pollution problem, paradigm shifts in policy did not occur until the EC was added into the policy network from outside. The 'shock' that resulted from the UK failing to meet EC standards and being forced to appear before a European court was enough to force a change in the dominant advocacy coalition.

The advocacy coalition approach has its limits however; boundaries between coalitions are often unclear, and conflicts occur between agencies that share the same core beliefs (Bulkeley, 2000). Hajer (1995b) advocates a "*discourse coalition*" framework as an alternative, suggesting that "*actors ... create the world*" (Hajer, 1995b) and it is the *storylines* that they draw on to describe the issue at hand that are used as the base for *discourse coalitions.*

The concept of discourse coalitions is flexible and allows an individual actor/institution to frame the issue at stake in a different manner depending on context. Bulkeley (2000) illustrates this with examples from the Australian Climate Change Policy Network. In this she highlights two initial discourse coalitions, each consisting of actors with very different core beliefs to the other actors in the same coalition, but using the same storylines to argue for policy change.

The first of these is the "greenhouse action discourse coalition", consisting of both scientists and green action groups, who, despite sharing very different outlooks on the ability of science to explain the problem, frame the climate change issue in terms of

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[7] *Discourse* is used as a term to describe the way that an issue is framed for discussion: the "storyline" they use – different organisations may draw on different themed storylines to describe the same issue.

"the need to take a precautionary approach" (Cf. HoC Environment Committee in Hajer, 1995 in 2.2.1d). Furthermore, the insurance industry has the same outlook and discourse coalition but its concerns are for future economic, rather than ecological loss. The second group, the "resource based discourse coalition", frame their debate in terms of *"the need to act in the (economic) national interest"* and are, compared to the disparate greenhouse action discourse coalition, relatively cohesive in basic core beliefs (see also CEGB debate in Hajer, 1995 in 2.2.1d).

Bulkeley (2000)'s investigation of the "no regrets" storyline, where "*measures that were cost effective on energy grounds alone, so that any environmental benefits ... would be free*" (Wilkenfield, 1995) showed that by shifting their discourse the two coalitions could work together to form a "coalition of convenience" and influence policy change. Thus, rather than needing the external shock to change a dominant advocacy coalition, policy development was influenced by the two discourse coalitions mentioned above joining forces in a new discourse.

In this thesis the network theory approach is a tool for interpreting the relationships between stakeholders in terms of how different coalitions form around the issues of the "forest effect", and how/whether these coalitions work to influence policy and practice.

2.2.1f Modes of Governance

This thesis explores how network relationships not only influence policy makers but also land managers responsible for implementing policy. In doing so it is necessary to consider the different pressures that exist to guide stakeholders. Tenbensel (2005) summarises four mechanisms by which "governance" or "steering" pressures are applied to individual actors drawing on the metaphor of the suits in a pack of cards. Table 2-2 outlines the four suggested steering methods Hierarchy (♠), Markets (♦), Professional networks (♣; which Tenbensel refers to as provider-based networks) and Community governance (♥). He builds on this metaphor to stress the point that different modes of governance or techniques of steering will vary depending on the context and that whilst "*Governments have continued to adopt hierarchical (spades) mechanisms of steering, but increasingly ... they have substituted this with mode with diamonds, clubs and hearts"* by allowing professional networks, market pressures (competition) and/or community engagement to guide decision making. He stresses also that "*governments are not the only ones capable of deploying multiple modes. Other participants in public management 'games' including NGOs, community groups and frontline officials use different combinations of suits in order to assist or resist state attempts to steer*" (Tenbensel, 2005).

Table 2-2 The four "modes of governance" suggested by Tenbensel (2005) using the metaphor of a pack of cards.

Suit	Mode of Governance	Knowledge/ Power	Sources of knowledge and power
♠	Hierarchy	Knowledge-base used	Draws on "epistemic knowledge": that generated by applying analytic rationality and scientific method.
	"Follow the rules"	Source of Power	Power is drawn from "legal-rational authority that resides in agencies of the state"
♦	Market	Knowledge-base used	Draws on the costs/benefits of the decision in question
	"Act in best interest"	Source of Power	Power when decisions of the consumer influence the resource available for governance.
♣	Professional networks	Knowledge-base used	Draws on practical knowledge of "what works on the ground".
	"Follow network pressures"	Source of Power	Can influence change by determining the ways and conditions under which services are delivered
♥	Communities	Knowledge-base used	Draws on a wider 'community' knowledge of "what is right for us".
	"Do what's in communities' interest"	Source of Power	Sources of power include populist movements such as lobbying and community activism.

In terms of this thesis the interest in modes of governance is in the extent each of these pressures is a factor determining how stakeholders within the network around the "forest effect" adopt a course of action. Are the hierarchical policies reflected directly in land management practice[8] without any influence from the professional networks, market drivers or community pressures within which the practitioner is embedded? To what extent do other stakeholders influence practice, and what mode of governance is required for their views and knowledges to be included?

2.2.1g Conclusion: Positioning the thesis

In this thesis I take a pragmatic (weak) constructivist stance: my interest is in the insights, implications and analytical tools that can be drawn from a constructivist interpretation of science and its role in decision making. This stance (highlighted in blue in Table 2-1) equates to an ontological *belief* (I can't prove it) that there is a "real world" but that "facts" "truth" and "knowledge" are social constructs impacted by human choices that change with individual and context. Relativism is avoided by the fact that I see the outcomes of these choices as very real and significant in terms of their (socially constructed) impacts on both the "real world"/environment and the people who depend on it; some actions are *better* for some actors than others. It is the role of socially

[8] I refer to *practice* as the end result of the policy process (e.g. in practice), rather than the day to day practice of forest practitioners (e.g. forest practice)

constructed knowledge in this decision making process that is of interest to this thesis. Like Jasanoff (2003), the key questions for me are: *How is knowledge created and by whom? Whose knowledge is included and why? Whose is excluded and by whom? What impacts does this have on the way that the environment is managed to address the problem of acidification?* These questions are reflected in the research questions in Section 1.1.1.

2.3 This Study

2.3.1 Overall Methodology

This thesis draws on the ideas of Social Learning (see Section 1.3.2a) and the role of Best Available Knowledge in the management of the "forest effect". To do this the overall methodology for the thesis was designed to collect and analyse both *qualitative* information on the knowledges of multiple stakeholders and *quantitative* best available science (Section 1.3.2). As Prell *et al.* (2007) stress for complex issues of common pool resource management such as the "forest effect" the problems "*should be identified by the stakeholders themselves*": this thesis is based in a "participatory" methodology. In doing so, I draw on the emergent trend of projects such as the UK "Rural Economy and Land Use" programme (RELU; e.g. Dougill *et al.*, 2006; Prell *et al.*, 2007; Reed *et al.*, 2008) the EU-funded "Social Learning for Integrated Management and sustainable use of water at a catchment scale" (SLIM; e.g. Blackmore, 2007; Collins *et al.*, 2007; Ison *et al.*, 2007) as well as approaches adopted by international environment agencies (such as the European Environment agency; Alcamo, 2001) who all found their approaches to Best Available Knowledge firmly in a stakeholder-based methodology. For this project a group of key stakeholders including policy makers, forest managers, environmental regulators and representatives of "interested parties" was identified in Galloway Forest District, one of the most significantly acid-impacted areas in the UK (see section 2.3.2).

2.3.1a A note on thesis structure

The structure of the thesis is more complex than the traditional model and contains two sections on methodology within its overall structure. By working with stakeholders, the problems surrounding the "forest effect" are a) identified from stakeholder perspectives, and then b) targeted for research later in the thesis. The methodology sections for these two stages are separated within the thesis.

The first introduces the stakeholder-based methodology that frames the thesis as a whole, including the stakeholder group, the study area and the methods by which sociological data on the knowledges of multiple stakeholders' were collected. The three following chapters (Chapters 3-5) draw on these data to investigate the evolving relationships between stakeholders, science, policy and practice.

This stakeholder-based foundation is then used to guide the methodological approach to the analysis of *best scientific data*. As a result, at the end of Chapter 5, insights drawn from *stakeholder knowledge* are summarised and the role of science in answering the key questions raised by an analysis of stakeholders' knowledges is discussed. The second methodology section is found in Chapter 6 and focuses on both interdisciplinary and natural science methodologies that are brought in to address these questions in chapters 7-9.

2.3.2 The Study Area

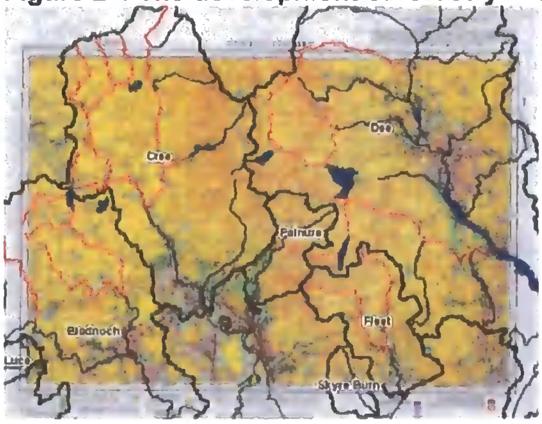
2.3.2a Selection Rationale

The aim in selecting a study area was to find a location where there was a significant history of the debates surrounding the "forest effect". A review of the academic literature reveals that the key areas of focused study are Plynlimon (Ormerod and Edwards, 1985; Reynolds *et al.*, 1986) and Llyn Brianne (Stoner and Gee, 1985; Ormerod *et al.*, 1989) catchments in Wales; and Galloway (e.g. Wright *et al.*, 1980; Battarbee *et al.*, 1985; Harriman *et al.*, 1987) and Loch Ard (e.g. Harriman and Morrison, 1982; Kreiser *et al.*, 1990) in Scotland. Of these, Galloway in South West Scotland was preferred as Durham University had both existing contacts (see 2.3.3b) and existing data (both water chemistry and satellite imagery from Puhr, 1997; ForestSAFE, 2003) within the region.

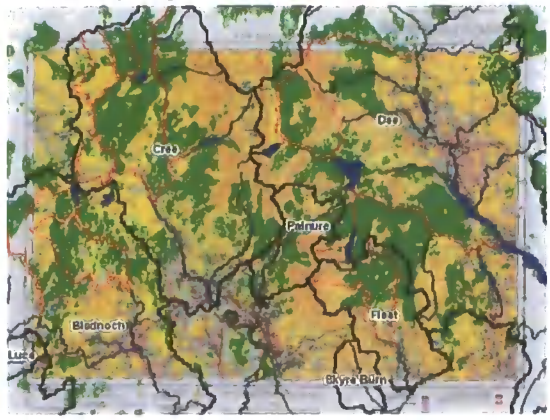
2.3.2b Galloway Forest District

Galloway Forest District in South West Scotland is one of the most heavily afforested areas of the United Kingdom, and an area that has undergone a dramatic change in land use since the end of the Second World War. The first land utilisation survey (Figure 2-1a) shows the predominant land use c.1932, as being "heath, moorland, commons and rough pasture". In 1947 the bulk of the planting began, and now the forest district (Figure 2-3b) is the largest in the UK covering some 97,000 ha of the Scottish countryside (Forestry Commission, 2006a), the majority of which is managed by the Forestry Commission. Figure 2-1 gives an impression of the scale of this change.

Figure 2-1 The development of forestry in the Galloway region 1932-1995



a) 1932: First Land Utilisation Survey. Yellow =health/moorland category)



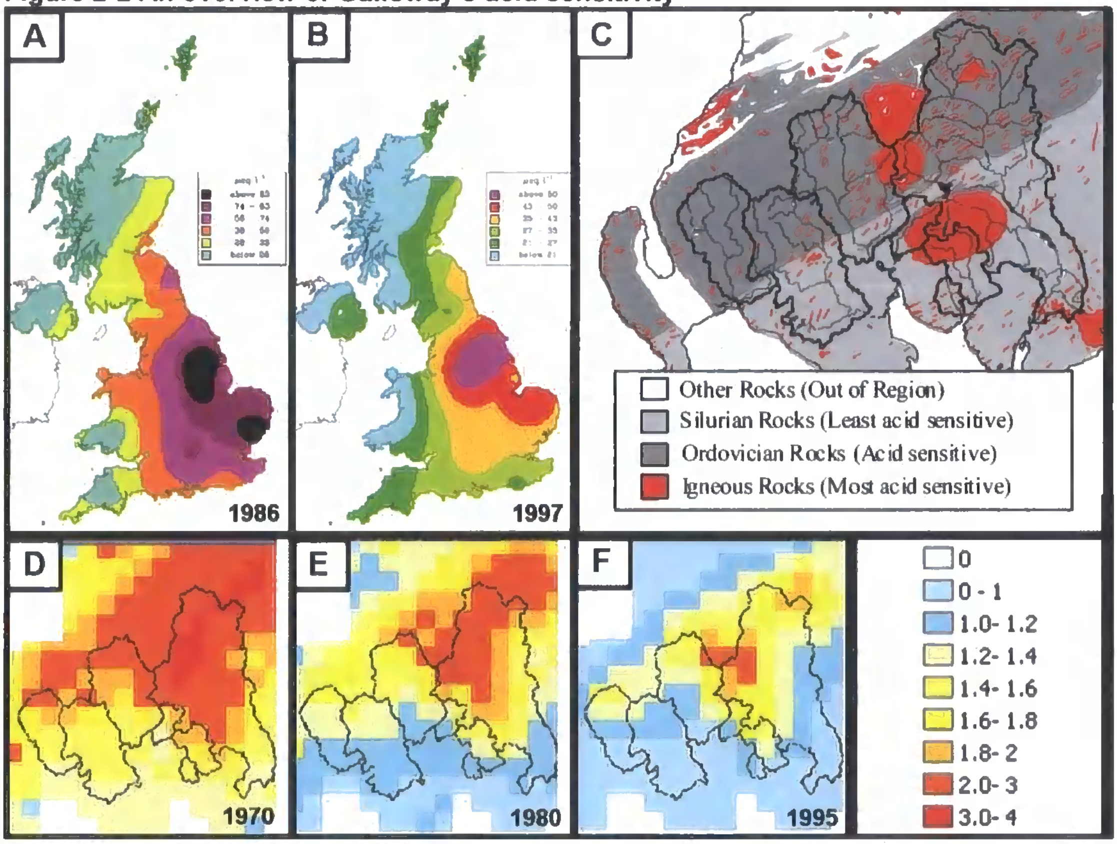
b) 1995: Green = Canopy-closed forest cover from Landsat Imagery (see Chapter 6).

Whilst this dramatic change of land use has brought with it numerous benefits to the area: *"The Galloway Forest Park is one of a relatively small number of visitor destinations that underpin economic activity in accommodation, catering and retail"* within the region (Forestry Commission, 2006a), the "forest effect" has led to 30 years of heated debate over the impacts that forestry has had on the freshwater ecosystem and particularly fisheries interests; controversies that have continued to the present day. This study focuses on seven catchments within the Galloway region, of which the major catchments are the Luce, Bladnoch, Cree, Fleet and (Solway) Dee (Table 2-3).

2.3.2c Galloway: Acid Sensitivity

In comparison with the UK as a whole, Galloway receives relatively small inputs of sulphate (Figure 2-2A and B). The geology of the region (Figure 2-2C), however, makes the area naturally acid sensitive; both the Ordovician and igneous extrusions that cover the majority of the upland area of catchments within the region are particularly vulnerable to small changes in acid input. Figure 2-2D-F show the modelled distribution of total sulphur deposition as it varies regionally and through time (see Chapter 6 for more detail). The combination of higher deposition and more sensitive rocks makes the eastern areas (Dee, Palnure and Fleet) the most *acid sensitive;* although the loss of fish stocks has been widespread and significant across the region.

Figure 2-2 An overview of Galloway's acid sensitivity

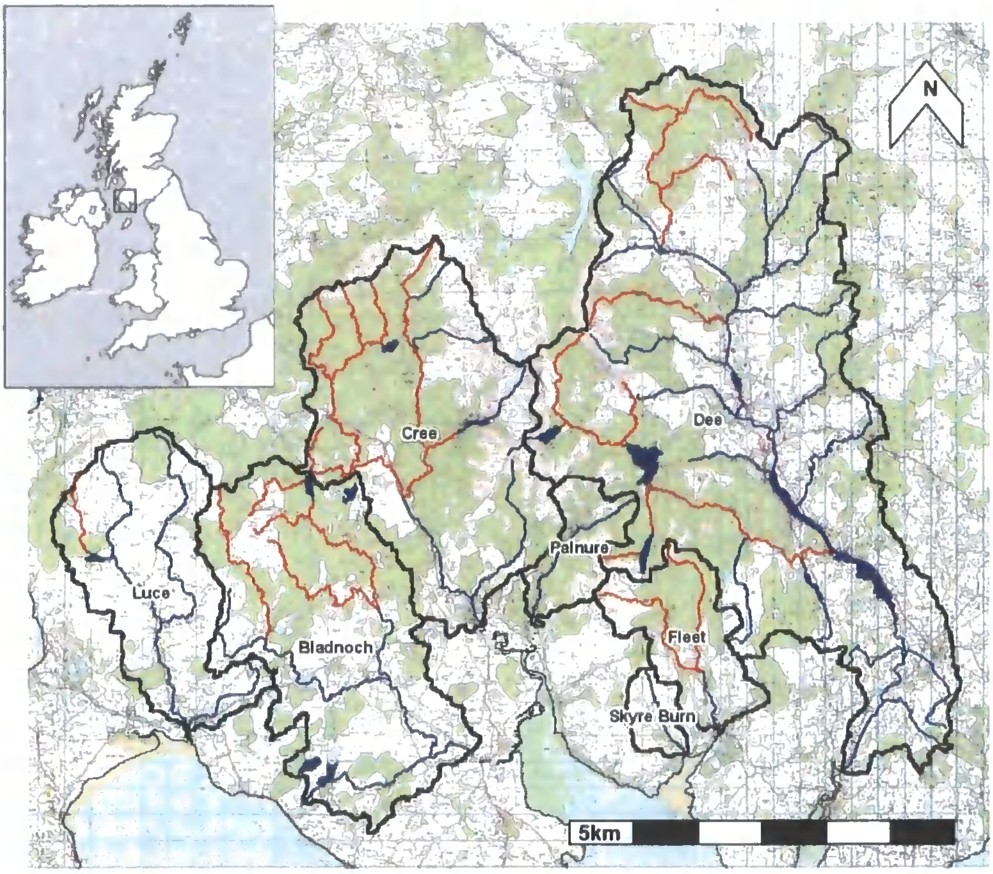


A: 1986 and B: 1997 non-sea salt SO_4^{2-} concentration in rainfall ($\mu eq\ l^{-1}$) modified from NEGTAP (2001).
C: Geology from British Geological survey, 1:625,000 (BGS, 2007)
D: Total Sulphur 1970 E: Total Sulphur 1980 F: Total Sulphur 1995 (all total deposition* keq $ha^{-1}y^{-1}$ S source: Centre for Ecology and Hydrology)

The Cree (see Figure 2-3), for example, described in 1981 as being a "healthy" river system with "*good runs of fish*" (Mills and Gasser, 1981), was discovered in 1988 to have entirely "*lost its once substantial run of salmon*" in its upper reaches (Stephen, 1988) . Similar changes have also been identified for the upper reaches of the rivers Bladnoch, Fleet and to a lesser extent the Luce (Galloway Fisheries Trust, 1989-1996). This is recognised by the Scottish Environmental Protection Agency (SEPA) and the "forest effect" was highlighted[9] as a threat to large proportions of the rivers within the region (Figure 2-3) meeting the requirements of the European Union (EU) Water Framework Directive (see Section 1.3.1). Of these, it is the lowland rivers Bladnoch, Cree and Fleet, all key fishing rivers, that are most affected, with over 50% of their respective reaches identified as at risk (Table 2-3).

[9] Note these are the initial characterisations and not the final designations: see Chapter 6

Figure 2-3 Forestry impacts on acidification in Galloway Forest District



OS 1:10,000 Raster © Crown Copyright/database right 2007. An Ordnance Survey/(Data centre) supplied service.

Table 2-3 Length of river classified by SEPA as affected by forest enhanced acidification.

Catchment	Total Length	No Forest Impact (NF/2b)		Forest Impact on Acidification (1a/1b/2a)	
		km	%	km	%
Bladnoch	128.0 km	**62.4**	*48.8*	**65.6**	*51.2*
Cree	133.9 km	**46.9**	*35.0*	**87.1**	*65.0*
Dee	324.3 km	**220.1**	*67.9*	**104.1**	*32.1*
Fleet	34.4 km	**6.1**	*17.9*	**28.2**	*82.0*
Luce	74.4 km	**66.8**	*89.7*	**7.6**	*10.3*
Skyre burn	8.3 km	**8.3**	*100*	**0**	*0*
Palnure burn	16.4 km	**0**	*0*	**16.4**	*100*
All Rivers	**720.0 km**	**410.8**	*57.0*	**309.2**	*42.9*
SEPA classification in terms of potential to pass/fail the WFD. Only rivers listed here included in "All Rivers" category					

2.3.3 The Stakeholder-Based Approach

2.3.3a Constructivism and Subjectivity

The "forest effect" in this thesis is conceptualised as a subject of an evolving learning process around an uncertain environmental issue, rather than something knowable with a single definite explanation. This conceptualisation follows a socially constructivist philosophy and draws on the Social Learning approach; in doing so, it must be recognised that the work presented within the thesis is necessarily a subjective interpretation resulting from my own interaction with the data sources I actively selected to inform my viewpoints. This is not however to say that the selected approach is "merely" subjective (Crang and Cook (2007). As discussed in Section 2.2.1, objective scientific methods are *"just as socially grounded, conditional, and value laden as the other"* (Wynne, 1992). Crang and Cook (2007) argue that *"the task for* all *researchers is to recognise and come to terms with their partial and situated subjectivity rather than aspire to an impossibly distanced objectivity"* and that by achieving this *"subjectivity is much less of a problem and much more of a resource for deeper understanding"*. Subjective research is unavoidable, but this, they stress, does not mean that it cannot be rigorous, systematic and convincing (Cook and Crang, 2007).

To achieve this, they argue for the importance of three factors:

- *Theoretical Adequacy*: The research method must consider itself in relation to the approaches taken in other studies so as to understand the similarities with and differences from others. *"For a researcher to have confidence that his/her study has been rigorous enough he/she must have sought out and explored the tensions and commonalities between multiple perspectives on the research problem i.e. [their own] and other people's"* (Cook and Crang, 2007 referencing Schutz, 1967)
- *Theoretical Sampling*: the research method must target not the greatest number of people, but the sample must be representative of the key positions within the debate of interest: *"It is not the sheer number 'typicality' or representativeness of people approached that matters, but the quality and positionality of the information that they can offer"* (Cook and Crang, 2007 referencing Geiger 1990; McCracken,1988).
- Theoretical Saturation: The research method requires that a point is reached where *"you have heard the range of stories that people within the community have to tell you about their experiences and explanations of what is happening to them"* (Burgess, 1992;Cook and Crang, 2007). If this point is reached there is no need for the inclusion of further stakeholders.

The following sections detail the methodological approach taken in this project with the aim of being "rigorously subjective" in mind. Effort is also taken to introduce context (relationships between stakeholders, and my own positionality) where it is felt that these factors may have impacts on the interpretations that are drawn.

2.3.3b Stakeholders: Who's in and why?

The focus of this project is determining the extent to which policy (the Forest and Water Guidelines) and practice (of the Forestry Commission in the case study area) are based on the Best Available Knowledge of the environment: the aim in selecting the stakeholder group for this thesis was therefore to include the variety of differently positioned viewpoints focussed on the roles of collecting knowledge for the purposes of influencing the formation of policy. So as to assure an adequate theoretical sampling and approach to theoretical saturation whilst assuring that the group was small enough to be manageable within the constraints of one thesis. To achieve this a sampling strategy was followed that targeted four key roles: a) **Policy Makers**: those who created the policies for mitigating the "forest effect"; b) **Forest Managers**: who implemented these policies; c) the **Environmental Regulator** with the responsibility of assuring that environmental targets of these policies were met; and d) independent **"interested parties"** whose claims to the environment would be impacted by land management. To maintain a tight group focused on the management of the "forest effect" external research scientists were not included within the stakeholder group. The extent to which the knowledge produced by these scientists is integrated into the Forest and Water Guidelines is discussed in chapters 3, 4 and 5.

Table 2-4 Project stakeholder overview.

		Interest		Influence		Knowledge		
		Role	Interest in "forest effect"	*FWGs* Panellist	Power over Local Practice	Empirical Data	Local Knowledge Galloway	Job Start Year (approximate)
FCH†	**Forestry Commission Hydrologist**	**PM**	✓	✓		✓	(✓)	**1987**
FC-PP†	Chair of the *Forest and Water Guidelines* panel; Specialist Advisor to the FC at GB level.	PM	(✓)	✓				1998
FC-G	**Galloway Forest District Manager**	LM	✓		✓	(✓)	✓	1999
SEPA-G	**Team leader of local SEPA/SRPB (retired Nov 2005); SEPA *Forest and Water Guidelines* panellist**	ER	✓	✓	✓	✓	✓	1976
SEPA-NS	**Replaced SEPA-G as team leader of local SEPA/SRPB**	ER	✓		✓	✓	(✓)	2005
SEPA-WFD*	SEPA Water Framework Directive implementation team member	ER	(✓)				✓	1998
GFT-X*	Ex-GFT Senior Biologist	IP	(✓)				✓	1991
GFT	**Galloway Fisheries Trust Senior Biologist (current)**	IP	✓			✓	✓	1998
GFT-S	GFT Stakeholder; Local Landowner & fisheries interest	IP	✓				✓	1960

ROLE: PM = Policy Maker, LM = Land Manager, ER=Environmental Regulator, IP=Interested Party
✓ Yes (✓) Some † Interviewed at the same time * same person

By choosing these roles, the intention is to sample the breadth of available viewpoints so that including additional parties would not greatly increase the stories and explanations of the "forest effect" available (Burgess, 1992). Within these roles multiple stakeholders were targeted; however, stakeholders were involved with the project to different extents and one key stakeholder from each group, was identified and used as a continual point of contact. In terms of representing the policy makers behind the *Forest and Water Guidelines* guidance on acidification ((a) in the list above) this contact was the Forestry Commission Hydrologist and for the Galloway stakeholders (b-d) this individual was the most senior representative of the targeted organisation. The aim in selecting these key stakeholders was to sample the institutional view most likely to be represented in practice. Additional stakeholders beyond these four key roles were also identified to provide context.

Table 2-4 summarises the stakeholders included in terms of their role, influence, interest and types of knowledge that they offer. The following section details each the stakeholder and organisation in more detail. It provides context regarding each stakeholder to identify: a) the reason for their inclusion; b) any specific information regarding the stakeholder that might be needed to interpret the views they present.

The impacts of the inclusion and exclusion of potential stakeholders from the project are also considered in the section that follows. Whilst the exclusion of any available knowledge is regrettable, it is my belief based on four years of research that the number of key stakeholders active in terms of influencing the "forest effect" in Galloway is relatively small, and that these stakeholders were included within this project. Whilst the excluded stakeholders may offer additional views, it is not expected that these will be outside of the range of opinions covered by the existing group. Keeping a tight stakeholder group allowed me to constrain the project well and develop a far more detailed and informative relationships with the key stakeholders than a wider more distributed project would have.

2.3.3b(i) Anonimity

All stakeholders provided their consent for the use of the interview material presented within this thesis on the understanding that it would be anonymised; this step has been taken and all stakeholders are referred to by a code describing their organisation and role. The individual stakeholders are introduced below.

2.3.3c The Forestry Policy Makers

As introduced in section 1.2.1c, the policy response that governs forest management to mitigate the "forest effect" is the *Forest and Water Guidelines*. These are developed by a panel chaired and with scientific guidance from the Forestry Commission and including SEPA, the Environment Agency, the JNCC (Joint Nature Conservancy Commission in this case represented by Scottish Natural Heritage: SNH) and consultations from many others. To capture a representative view of these policy guidelines three stakeholders were included within the stakeholder group.

FC-PP (Context only): Forestry Commission (Policy and Practice)

This stakeholder is included as the Chair of the Fourth Edition of the Guidelines panel and as such the person with the ultimate responsibility for coordinating the *Forest and Water Guidelines*. FC-PP holds a PhD and has a science background; however their role regarding the FWGs is as Specialist Advisor to the Forestry Commission. FC-PP acknowledged themselves that they relied heavily on the Forestry Commission Hydrologist for the purposes of making decisions regarding hydrology (see Chapter 3). After an initial interview in tandem with the Forestry Commission Hydrologist (at FC-PP's request), the Forestry Commission Hydrologist was used as the primary point of contact regarding the "forest effect".

FCH (Key Stakeholder): The Forestry Commission Hydrologist

The Forestry Commission Hydrologist is the key scientific advisor regarding the "forest effect" in the *Forest and Water Guidelines*. In addition FCH has significant long-term experience and has been working as a scientific advisor to the Forestry Commission since before guidance regarding the "forest effect" was included in the *Forest and Water Guidelines*. They were themselves involved in many of the debates in the late 1980s and early 1990s.

SEPA-G (Key Stakeholder): SEPA *Forest and Water Guidelines* representative

This stakeholder plays a dual role; they were both the SEPA member of the *Forest and Water Guidelines* panel and the Team Leader of SEPA in Galloway (see below). In the policy maker context they are included here as a representative of "non-Forestry Commission panellists". As such they are viewed as representing an environmental rather than forestry focus on the panel.

Issues of inclusion/exclusion

Neither SNH nor the Environment agency is included in the stakeholder group. This is not seen as a significant problem for the purposes of gaining an insight into the knowledge deliberation involved in the *Forest and Water Guidelines* decision making process as the SEPA representative is expected to represent similar perspectives to that of other environmental interests.

2.3.3d The Forest Manager

The majority of afforested land in Galloway is managed by the Forestry Commission, and the remainder is controlled by the Forestry Commission's *Forest and Water Guidelines*.

FC-G (Key Stakeholder): Galloway Forest District Manager

The Galloway Forest District Manager (FDM) has the overriding control over the Forestry Commission owned land within Galloway Forest District in terms of harvesting, planting, tourism and recreation. FC-G is employed by Forest Enterprise and tasked with the management of the Forestry Commission's estate and commercial activities; their overriding responsibility is to implement the Scottish Forestry Strategy. As the individual with the greatest influence over the Galloway forest park the FDM was seen to be able to provide an overview of what approaches would and would not be possible in practice.

Issues of Inclusion/Exclusion

Neither Private forestry nor actual forest practitioners were included in the stakeholder group. Regarding private forestry, it is argued that private forestry will adhere to the *Forest and Water Guidelines* (to which they are bound by financial contracts) and that exceptions to this are rare (a position supported by both FC and SEPA interviews; see Chapter 3). As a result, whilst Private Forestry has less legal requirement to be sensitive to ecological concerns than the Forestry Commission, its impact in practice will still depend on the *Forest and Water Guidelines.* As a result it is important to recollect at all times that whilst the Forestry Commission may be able to go "beyond the guidelines" not all forest managers will.

It should also be noted that a Forestry Commission conservator (with responsibilities for applying Forest Policy to the private sector) was also invited to the stakeholder meeting (held in chapter 7) at the request of other stakeholders. The conservator provides some context over how private forests are managed by the Forestry Commission, but was not interviewed or involved in long-term contact and so is not considered a major stakeholder within the project.

Forest Practitioners, those who cut down and plant the forests were seen to be outside the scope of the project. Although it is their actions that govern the impact of forestry on the environment it is assumed that their actions are directly governed by the *Forest and Water Guidelines* as modified by the orders of those in management. This stance is likely to be true for the most part, and actions outside management recommendation would need to be quite significant (planting/felling outside of the designated areas) to impact the "forest effect".

2.3.3e The Environmental Regulator

The environmental regulator is self-selecting: until 1996 the environmental quality of the waters of Galloway were regulated by the Solway River Purification Board (SRPB), granted its powers under the Control of Pollution Act 1974 as modified by the Water Resources Act 1991. After 1996 the Board was amalgamated into the Scottish Environmental Protection Agency (SEPA). In 2000 SEPA was named the responsible body for implementing the EU Water Framework Directive in Scotland, and in 2003 the Scottish Parliament's Water Environment Water Services (Scotland) Act put these powers into national legislation. Three stakeholders were chosen to represent the SRPB/SEPA.

SEPA-G (Key Stakeholder, until 2005): Team Leader, SEPA Newton Stewart
SEPA-G was the team leader of the SEPA team for Galloway, based in Newton Stewart, with over 30 years of experience of working with forestry and acidification in Galloway. As mentioned above, the SEPA-G was also the SEPA panellist on the *Forest and Water Guidelines*. SEPA-G therefore had: a) local influence over forest practice; b) national influence over forest policy; and c) significant local knowledge on the evolution of understanding around the "forest effect". SEPA-G retired at the end of 2005 but was still willing to be interviewed. It should be noted that this interview took place after this retirement which may have allowed more reflections on the evolution of the "forest effect" than other stakeholders with ongoing professional responsibilities.

SEPA-NS (Key Stakeholder, after 2005): Team Leader, SEPA Newton Stewart
SEPA-NS took over as team leader of the SEPA office SEPA-G's retirement in November 2005; from this point on SEPA-NS became the key SEPA contact. SEPA-NS had significantly less specific experience regarding the "forest effect" than SEPA-G and had had very little exposure to SEPA-G's knowledge. It should be noted that my presence as an outside "expert" may have had more influence on this stakeholder than on others as I had, at the point of the changeover, more experience regarding the

"forest effect" (in contrast to all other stakeholders in the project who all know far more than me).

The change between SEPA team leaders will have an influence on the local response of SEPA since the introduction of the *Forest and Water Guidelines* but not on the SEPA role in the Guidelines' creation or SEPA's role as represented in the interviews, all of which referred to the time before the change over.

SEPA-WFD* (Context Only): SEPA WFD Implementation Team member
The final SEPA stakeholder was a member of the SEPA WFD implementation team. SEPA-WFD* provided useful context for the project by detailing the approach that SEPA would take to the "forest effect" as a diffuse pollutant in relation to the WFD's drive for "good ecological status". It should be noted that the SEPA WFD stakeholder also had extensive experience of the Galloway region and the "forest effect" in particular having worked from 1991-1998 as a Fisheries Biologist for the Galloway Fisheries Trust (see below). In recognition of the fact that both SEPA-WFD* and GFT-X* are the same person interviewed in a dual role, they are marked with an asterisk when referenced. This stakeholder was only used for context, as, whilst interested, the remit of their SEPA work was at a national, rather than regional scale and the "forest effect" was not the focus of it.

2.3.3f The Interested Party

The previous stakeholders have all been from government institutions. To select the final stakeholders I wanted to focus on actors who had a significant interest in the "forest effect", and for whom the "forest effect" had a significant impact, but who had no governmental power or responsibility to address the problem. In Galloway the most outspoken interested parties involved in the "forest effect" have been fisheries interests. The Galloway Fisheries Trust, as an independent NGO set up to collect data to represent these interests, provided an ideal counterpoint to SEPA and the FC. Three GFT stakeholders were involved within the project

GFT-X* (Context Only): GFT Fisheries Biologist (1991-1998)
As mentioned above, GFT-X* (also SEPA-WFD*) was Fisheries Biologist for the GFT from 1991-1998 and had continued to live within the region after that point. As such they provided an excellent context regarding the evolving debates over the "forest effect" in Galloway from a fisheries viewpoint. They were only used as context for the reasons detailed above. Interviewing the same stakeholder under two roles is not seen to be a problem as the roles were clearly separated by time and the stakeholder

expressed no concerns about expressing problems from the different institutional viewpoints of their past and present roles.

GFT (Key Stakeholder): GFT Fisheries Biologist (1996?-ongoing)

GFT is the current Senior Fisheries Biologist of the Galloway Fisheries Trust. The stakeholder holds a Masters degree focusing on the impacts of forestry on Galloway rivers, the results of which were published in the academic literature in 1995. They have a relatively long-term fisheries perspective of the "forest effect" and experience working alongside SEPA and the Forestry Commission in the local context.

GFT-S (Context Only): Local Fisheries Interest

GFT-S is a local landowner who grew up in Galloway and used to own a fishery in an acidified catchment. This stakeholder provided a long-term view of the evolving "forest effect" from a fisheries perspective that was unique in that it was entirely independent of any working relationships with the Forestry Commission or SEPA.

2.3.4 Data Collection Methodologies for Stakeholder Analysis

With a base stakeholder group selected, methodologies from the social sciences including participant observation, textual analysis and semi-structured interviews

2.3.4a Participant Observation

Participant observation involves *"an immersion of the researcher's self into the everyday rhythms and routines of a community, a development of relationships with people who can show and tell the researcher what is 'going on'"* (Cook and Crang, 2007). The approach taken in this thesis does not follow the traditional ethnographic approach associated with participant observation; I did not "immerse myself" in the "everyday rhythms" of stakeholders lives; I did, however, over the period of four years, develop solid working relationships with the key stakeholders who informed me as to "what was going on". To do this, this research itself was the focus for the participant observation; by involving the stakeholders from an early stage I was able to gain a far better understanding of each stakeholder's approach to the "forest effect" and the relationships between participants than by any methodology based solely on interviews or historical data. The section that follows details how this was achieved in practice.

It should be noted that, whilst the qualitative and quantitative parts to this thesis are separated within the structure of the thesis, and the use to which the qualitative data were put is driven by the problems identified by the stakeholders, the actual data collection process was an important part of the relationship building process. In this way, whilst there is a clear distinction within the thesis between qualitative and quantitative data types, in practice the two approaches occurred in tandem; in the section that follows I reflect on the implications of this.

2.3.4b Making Contact

The work began in the winter of 2004 when initial e-mail contact was made. This process was facilitated by building on pre-existing relationships that derived from my own prior research work alongside the Galloway Forestry Commission as both a masters student (2001) and a research associate (from 2002-2003 e.g. ForestSAFE, 2003). Furthermore, existing relationships developed between one of my supervisors during the supervision of Chris Puhr's PhD work in 1995-7 (Puhr, 1997) meant that a) long-term stakeholders recognised a Durham University connection to the exploration of acidification, and b) contacts within the Galloway Fisheries Trust and SEPA were readily available. As a result it was relatively easy to gain access to the stakeholders and initial "probing meetings" were held in December 2004 to inform stakeholders about the project.

As mentioned above, a key focal point to these initial probing meetings was also discussion of the collection of a quantitative base-line of contemporary chemical data at a regional scale. This provided a solid basis for discussion as all stakeholders were aware of the previous 1995 survey (Puhr, 1997) and interested to know the state of the region's waters 10 years later on. By offering to coordinate the process and requiring the assistance of SEPA, the Fisheries Trust and the Forestry Commission for manpower, vehicles and resources, I became quickly recognised as a participant interested in the "forest effect". At the same time, I always stressed my interest in the role of policy and the importance of the relationships between stakeholders and often discussed this with stakeholders individually, keeping field diaries and notes as I began to progressively understand the ways that the three stakeholder organisations worked together; the first field survey was performed in March 2005.

Initial meetings with the policy makers were organised to coincide with a conference on the implications of the *Forest and Water Guidelines* for private forestry in New Lanark (January 2001). I met both the Forestry Commission Hydrologist and the Chair of the *Forest and Water Guidelines* panel (who I also knew from my previous work as a Research Associate). We discussed my research and agreed dates for a more formal "Policy Maker" interview; the Chair of the *Forest and Water Guidelines* panel preferred the interview to be a joint interview with the Forestry Commission Hydrologist and this was agreed.

2.3.4c Semi-structured interviews

As a means of consolidating the viewpoints that I was collecting through participant observation, semi-structured interviews were performed with the four key stakeholders and the three additional context setters. In creating my questions for each interview, I drew on my field notes and diaries, and in the case of the policy maker interview asked all Galloway stakeholders specifically if they had any questions that they wanted answers to. I had warned stakeholders during initial probing meetings that I would want to perform a recorded interview at a later stage, and that I might get them to repeat the things they had said to me informally. All stakeholders were happy with this, and as a result the interview process provided a means to formalise existing knowledge, and to provide comparable replies to key questions rather in addition to providing new information.

The interviews were based on a set of key questions ordered in themes, but around which discussion was flexible if the interviewee offered additional information of interest/relevance to the project. Although in some cases answers were already known, this was never reflected during the interview process leaving the stakeholders at liberty to respond as they chose. In asking the questions care was taken to remain as neutral as possible so as not to influence interviewee responses and questions were deliberately worded in open ended terms such as "to what extent ...?" to allow stakeholders flexibility to fit their responses to them. Whilst it is recognised that the views expressed by each stakeholder will be moderated by the audience, it is worth noting that the "official stance" of each stakeholder that is the interest within this project is well known by all others. The stakeholders have, after all, been debating these issues for almost 30 years (Chapters 3-5). Interviews were recorded and transcribed, and in the chapters that follows are referred to by the code for the stakeholder in brackets. e.g. "*quotation*" (FC-G).

2.3.4d Other Data Sources

In addition to interview data an array of documentary sources was also collected as a means to construct an impression of the "forest effect". These included not only the academic literature itself, which is an excellent historical documentary record of changing theories around the science behind the "forest effect", but published reports by the SRPB (Solway River Purification Board, 1970-1996) the GFT (Galloway Fisheries Trust, 1989-1996) and the Forestry Commission (Forest Research, 1980-1991). Although any such literature review will be partial, these resources provided significant additional information for the analysis in the following chapters. Furthermore it is recognised that official reports are necessarily biased and written with an institutional goal in mind. They are not seen as a definitive truth, but as an interpretation of events from one view. The presentation of these views in a publically accessible format means that the views presented are at least representative of those with which the organisation is happy to be linked. Individuals within the organisation may, of course, interpret the same situation in different ways.

Table 2-5 Timeline of key stakeholder interactions

		FCH	FC-PP	**FC-G**	**GFT**	GFT-S	GFT-X*/SEPA-WFD*	**SEPA-G**	**SEPA-NS**	Others
Dec 2004	e-mail contact established	✓	✓	✓	✓		✓	✓		
	Initial probing interviews			✓	✓		✓	✓		
Jan 2005	New Lanark Meeting : *Forest and Water Guidelines* v.4 to Private Forestry	✓	✓					✓		
Feb 2005	Galloway Field Survey Meetings	≈		✓	✓			✓		✓
Mar 2005	Field Survey			≈	✓			✓		✓
Apr-May 2005	Interviews (round 1)	✓	✓	✓	✓		✓			
Sep-Nov 2005	HIATUS 1: ForestSAFE									
Dec 2005	Galloway meetings			✓	✓			✓		
Jan 2006	Field Survey Meetings	≈		≈	✓			R	✓	✓
	Interviews (round 2)					✓			✓	
Mar 2006	Field Survey 2	≈		≈	✓				✓	✓
Apr 2006	Visit to Forestry Commission Hydrologist	✓								
Aug 2006	Forests for Water Conference Sweden	✓								
Aug 2006	Stakeholder Meeting	✓		✓	✓				✓	✓
Sep-Dec 2006	HIATUS 2: Overseas Institutional Visit									
2007 –ongoing	Phone/e-mail Contact	✓		✓	✓				✓	

R = retired ✓=direct involvement (they participated) ≈ = indirect involvement (from afar)

Table 2-5 shows a timeline of stakeholder interactions within the project. It details the timings of the interviews. Interactions after the last interview are not described in detail here as they are not seen to have had significant impact on the interpretations of results presented in this thesis. Whilst not detailing the total extent of my interactions with stakeholders, particularly the substantial level of phone and e-mail contact, Table 2-5 serves to acknowledge the extent to which stakeholder views continued to inform my knowledge.

2.3.4e A final acknowledgement of subjectivity

In concluding this chapter, I stress again the "rigorous subjectivity" (Cook and Crang, 2007), of the work presented here. It is unavoidable that decisions I have made will have affected the data collected and the interpretations that it is possible to draw. I have endeavoured in the sections above to address, where relevant, the factors where I believe my positionality, choice of stakeholder or selection of research method may have influenced the research. There are, however, bound to be a number of other more subtle factors that also influenced the process. I believe that the views stakeholders have reported to me reflect a sufficient theoretical sampling that the key parties involved in managing the "forest effect" in Galloway are represented, and that they can therefore be used as a basis for reflections on the relationships between science, stakeholders, policy and practice. I do, however, acknowledge that the interpretation of these views is my own: although I have attempted to rigorously ground these views in evidence, and I believe another interpreter with the same evidence would draw similar conclusions, I do not believe it is possible to achieve totally objective neutrality and so recognise that all reflections are influenced by the positionality of the researcher themselves.

2.3.5 Summary

This chapter has introduced insights from a social constructivist view of the science/decision-making process. It has stressed that an understanding of the factors that drive the inclusion and exclusion of knowledge in the decision making process is vital to understanding the ability of decisions (both of policy and practice) to be based on Best Available Knowledge.

It has also introduced the overall methodology that frames this thesis, and explained the method by which an understanding of multiple stakeholder knowledges was attained. The three following chapters (Chapters 3-5) draw on these data to investigate the evolving relationships between stakeholders, science, policy and practice and conclude with questions that drive the quantitative questions that are investigated in the remainder of this research.

Chapter 3 : Forest Guidance, "Forest effect".

3.1 Introduction

3.1.1 Chapter Overview

This chapter focuses on the *Forest and Water Guidelines*, the UK Forestry Commission's policy response to the issue of acidification. The chapter takes a long-term view from the identification of freshwater acidification as a UK problem in the late 1970s through to the introduction of the latest version of the *Forest and Water Guidelines* in 2003. Data are drawn from literature review and stakeholder interviews to explore three main topics:

1) The Forestry Commission's view of the *Forest and Water Guidelines*, their role as a tool for managing the impacts of forestry on water quality and the knowledge base on which they base their decision making.

2) The debate over acidification and the "forest effect" within the academic community: a review of the science of acidification, its ecological impacts and the methods and techniques used to identify areas at risk and the way that this science is reflected the *Forest and Water Guidelines*.

3) The changing institutional drives within the Forestry Commission and how this has impacted both forestry policy making and forest practice.

4) A worked case study summarising the impact of Forestry Commission guidance *in practice* on the management of Galloway Forest District prior to the fourth edition of the *Forest and Water Guidelines*.

The chapter ends with a discussion of the approach to knowledge taken by the Forestry Commission and the impacts this has had on knowledge transfer and thus the potential access policy makers and forest practitioners have had to Best Available Knowledge.

3.1.2 The Forest and Water Guidelines

3.1.2a The Forest and Water Guidelines, purpose and role.

The *Forest and Water Guidelines*, introduced by the Forestry Commission in 1989, represent the Forestry Commission's recognition that "*forests and their management can affect the quality and quantity of water moving through catchments*" (Forestry Commission, 2003b). The guidelines are not legislation; however, all land managed by the Forestry Commission is bound to adhere to the *Forest and Water Guidelines.* In addition, any forest planting supported by Forestry Commission Woodland Grant Schemes is also bound to the Guidelines; this includes the majority of private forestry.

"*[The Forest and Water Guidelines] are pretty much universally applied, there is the opportunity for individual operators to take forestry outside the scale of the guidelines but to do that means they wouldn't have access to public grants ... so it doesn't actually happen in practice.*" (SEPA-WFD)

In addition, in Scotland the Scottish Environmental Protection Agency treat them as legislation and any forester taken to court by SEPA "*would not be able to argue legally if they had not followed the guidelines*" (SEPA-G).

Furthermore as a response to the EU Water Framework Directive in 2004, it became the intention of both the Forestry Commission and SEPA that the portions of the guidelines that are mandatory should be extracted to a set of General Binding Rules which would become legislation, and allow SEPA to prosecute if broken (SEPA-G; FC-G; FC). In terms of the Water Framework Directive, it is very clear that the Forestry Commission see that the procedures set down in the *Forest and Water Guidelines* demonstrate that the Forestry Commission is meeting its role as a responsible body for the purposes of the WFD.

"*We see, in terms of the Forestry Commission, we're fairly at the forefront in terms of developing best practice to deal with diffuse pollution... we feel we've got a good set of guidelines in place that are best practice. So, when it comes to the Water Framework Directive approaching, [the Forest and Water Guidelines] identify sites that may fail to meet good status [as well as] the risk assessment process and the programme of measures to be considered to deal with that risk*" (FCH).

The Forestry Commission is proud of its achievements in the field of guidance for mitigating impacts to water quality. They stress that they have learnt from past mistakes, and built up an approach to water management that puts them at the "*forefront*" (FCH) in terms of both working with water users, and at a catchment scale. They stress that they have repeatedly refined their guidance to match growing concerns and increasing scientific knowledge. They are very keen that it be recognised that other land uses such as agriculture are in a much worse position, and that as a result they are confident that they will have to make far fewer adjustments in order to meet the needs of the WFD.

"*We've gone through revisions, and learnt from practice and research; we've honed down to a good set of guidelines to effectively protect freshwater environmental systems ... therefore presumably we don't have to go as far down the road as agriculture may have to, to deal with the risks. We'd like to think we've done a great deal to minimise the risks.*" (FCH)

3.1.2b Forest and Water Guidelines: a defensible line

The Forestry Commission does recognise that criticisms of the *Forest and Water Guidelines* exist, but indicate that they find themselves needing to mediate between two different extreme views: "*One was from the Fisheries Trusts, particularly in Scotland who felt that we hadn't gone nearly far enough and, as you can imagine, the woodland owners, particularly in the South West [of Scotland] felt that they were being unnecessarily restricted.*" (FC-PP)

The Forestry Commission, in response to these competing views, defends their decisions in terms of the *Forest and Water Guidelines* with two arguments:

Their first argument is that they "*stuck firmly to the view that [the Forest and Water Guidelines] had to be scientifically based*" (FC-PP), stating that "*you have to have a line you can defend otherwise we're just battered from one side by fisheries interests and the other side by forestry interests*" (FC-PP). In doing so the Forestry Commission shows themselves to be of the belief that a stance based on science is legitimate as a means to mediating in debates around the environment. This is in contrast with the social constructivist arguments (e.g. Wynne, 1992; Foucault, 1980; Ison *et al.*, 2007) discussed in section 2.2.1. Furthermore, they state that whilst science is the best tool for mediation, having the guidelines apply to the whole forest estate would be a "*huge task*" (FCH) and that pragmatic concerns need to be taken in to consideration to ensure that the Guidelines are practically applicable. As a result they follow a "*practical approach ... focussing on risk*" (FCH). The risk-based approach taken is discussed in section 3.2.6 and cannot therefore be seen to be purely following best available science: the extent to which this is a factor that inhibits access to Best Available Knowledge, will depend on the areas the approach identifies as at risk (discussed for 1978-2003 in section 3.3), and the extent to which these match with other knowledges: this is discussed in Chapter 3 :.

Their second argument is that the *Forest and Water Guidelines* were not, and never have been, created by the Forestry Commission on its own: "*The review group put together for this revision was a joint group... it wasn't just the forestry commission saying 'we think the 300m contour is fine we'll go with it' we were all signed up to it; it's a jointly badged document*" (FCH). Instead, the guidelines are created by a working group with members from environmental regulatory bodies; the fourth edition working group which included the Forestry Commission (FC-PP, FCH), SEPA (SEPA-G), the Environment Agency, the Joint Nature Conservancy Council (represented by Scottish Natural Heritage) and the Northern Irish Forestry Commission. The involvement of a wider stakeholder group than the Forestry Commission alone will provide the decision makers with access to a wider knowledges than those held within one institution: the extent to which "jointly badged document" is a factor influences the inclusion of Best Available Knowledge in the policy making process is discussed in sections 4.3 and 5.3.2c

3.1.2c Summary

In summary, the Forestry Commission sees the *Forest and Water Guidelines* as:

- Scientifically based, and defensible as a result;
- At the forefront in terms of best practice for the purpose of minimising risk to water courses;
- A sufficient tool to sites that may fail to meet good status for the purposes of the WFD;
- Defensible because they are a "jointly badged document" supported by a variety of actors.

It is in the light of these views that the following two chapters evaluate the relationship between knowledge related to the "forest effect", forestry guidance, forestry practice and the water environment. This chapter (Chapter 3 :) explores the history of the relationship between the scientific understandings of the "forest effect" and forestry guidance and evaluates the impact of the first three editions of the *Forest and Water Guidelines* for Galloway Forest District. Chapter 4 : focuses on the fourth edition of the *Forest and Water Guidelines* and draws on stakeholder interviews in Galloway Forest

District to explore the relationships between local understandings of the "forest effect" with the areas at risk identified in the *Forest and Water Guidelines*.

3.2 Identifying the "Forest Effect"

3.2.1 Introduction

3.2.1a The "Forest Effect"

In this thesis the term "forest effect" is used to refer to the mechanism by which forestry contributes to the acidification of water courses. It is used as a term with a shifting meaning that varies depending on the user and time.

3.2.1b The "Acid Rain debate"

As discussed in section 1.2.1c the identification of the "forest effect" has its roots in a much wider debate that was prevalent in the UK in the late 1970s and through the 1980s. The debate was focussed on whether or not "acidification" was an issue in the UK and, if it was, what were its causes. Scandinavian and North American scientists had initiated the debate in the late 1960s and early 1970s with a growing awareness that freshwater lakes were becoming acidified, and their fish stocks depleted (Jensen and Snekvik, 1972; Almer *et al.*, 1974; Wright and Gjessing, 1976; Beamish, 1974; Odén, 1968).

In the UK, however, the impacts had yet to be identified and it was only under pressure from Scandinavian countries who attributed the change to "long-distance transported acidic compounds from industrial countries upwind, including the UK" (Battarbee, 2004 referencing Oden, 1968) that the UK government found itself needing to take a stance on the debate (Battarbee, 2004).

The "acid rain debate" that followed is reviewed in Battarbee (2004); the elements that refer to forestry are discussed in detail below. However, a brief summary is as follows: In 1980 Wright *et al.*, using a combined water chemistry and gill netting survey of the Galloway region, identified that acidification was indeed taking place in the UK: with impacts on fish stocks (Wright *et al.*, 1980). This was attributed to "the deposition of strong acids from the atmosphere" (Wright *et al.*, 1980).

In response, the Central Electricity Generating Board (CEGB), supported by the science of Rosenqvist (1978) and some UK evidence of forest impact on fisheries (Harriman and Morrison, 1982; Stoner and Gee, 1985), argued that it was land use change, and not sulphate deposition, which was the primary cause of the acidification of freshwaters. Diatom studies (listed in Table 3-2) showed convincingly that the acidification of some lochs (Loch Grannoch, in Galloway) commenced prior to afforestation (Flower and Battarbee, 1983); suggesting that the primary *cause* of freshwater afforestation could not be forestry. The CEGB's argument was finally quashed in 1987 by Margaret Thatcher's decision to accept the Scandinavian position and sign to the UNECE Convention on Long-Range Transboundary Air Pollution (CLRTAP; see 1.2.1).

3.2.1c Acidity and Ecology

The growing recognition of acidification brought with it a need to understand the impacts on ecology: what was it about these acid waters that were leading to the impacts on fish that were being identified in acidified areas? Morrison(1988) provides a review of these issues, summarised in Table 3-1. The key points are that acidification leads to decreased pH and higher aluminium levels in freshwaters and that these are detrimental to both the hatching of fish eggs and the survival of adult fish. As pH decrease to approach pH 5 the risks increase; below pH 4.5 they are highly significant. Harriman (1988) suggests, as a result, that a pH of 5.5 should be considered as "biologically critical". The concept of a biologically critical level of pH was later replaced by the critical loads methodology (Nilsson and Grennfelt, 1988) which aimed to quantify the level of exposure to pollutant that a target organism could endure; this methodology is discussed in detail in Sections 3.2.5e and 3.2.6a.

Table 3-1 Summary of acid impacts on ecology

Impact	Detail
Salt balance pH<5	Decreasing pH affects the salt balance of both fish and some invertebrates, for fish, sodium may be lost from the body more quickly than it is taken up by the gills when pH approaches 5. Increases in calcium and salt can reduce this impact. Reference: (Muniz *et al.*, 1984; Sutcliffe and Carrick, 1973; McWilliams, 1982)
Hatching enzymes pH<4.5	pH of less than c.4.5 inhibits hatching enzymes leading to failed eggs. Reference: (Haya and Waywood, 1981)
Increased Labile Aluminium pH ≈5	Aluminium is most soluble in water at around pH 5. Labile aluminium has a similar affect on fish in terms of salt balance to low pH. Invertebrates are more resilient, but are also impacted. Aluminium has also been shown to lead to mucus build up on fish gills, leading to respiratory problems. It is only the labile form that is toxic and complexation of aluminium with dissolved organic matter can reduce this impact. Reference: (Muniz and Levistadt, 1980)

3.2.2 The Forestry Commission

3.2.2a Forestry Commission during the acid rain debate

During the acid rain debate the Forestry Commission took an epistemologically similar argument to that of the CEGB shown in Hajer (1995)'s case study (see section 2.2.1d) and stressed the *uncertainty* of the evidence for a "forest effect". Forest Research Reports from the time stressed that "*the relative importance of acid rain, forest cover and forest management practices has to be established so that forest managers can be advised on the best ways to prevent or reverse deterioration where it occurs*" (Binns, 1983) and recognised "*the increasing awareness of the acidification of fresh waters in parts of South West Scotland and central Wales*" (Binns, 1984).

As a response to this uncertainty the Forestry Commission involved themselves in numerous "collaborative" and scientific projects that focused on "*the inter-relations between water quality on the one hand and geology, acid deposition and land use, including forestry on the other*" (Carnell, 1986). These are listed in Carnell (1986) and include work at Llyn Brianne, Hafren Forest and Blaquhidder in Wales as well as Loch Ard in central Scotland and Lochs Fleet and Dee in Galloway; of these, the Loch Dee project is discussed in section 4.4.1d(i).

No guidance was however provided by the Forestry Commission itself prior to 1988 in terms of any approaches to minimising forest impacts on water quality. The closest document to guidance was "The Management of Forest Streams" (Mills, 1980) published in the Forestry Commission's "leaflet" series but written by Derek Mills of the University of Edinburgh rather than by the FC itself. It outlined "*a healthy stream and the needs of its fish*" in the light of forest management practices of ploughing and drainage; planting; fencing; road construction; spraying; application of fertilisers; fire; and thinning, felling and extraction. It provided information on means of stream improvement and introduced the notion of buffer zones. Acidification, only just coming to the fore at this time, was not raised by Mills.

By 1988, the Forestry Commission began to perceive that "*the association between forests and increased surface acidification in sensitive areas has been accepted by many as cause and effect*" and that this was beginning to have "*serious implications*" and "*restrict future afforestation*" in these areas (Nisbet and Binns, 1988). The Commission continued to stress the uncertainty: "*evidence for such a causal relationship [is] currently being assessed*". Implicit in this is the argument that there should be no change in management until the "*research of the impacts of different* *forest practices on water quality, including the effectiveness of remedial measures [that were] being conducted*" was complete and the problem was scientifically understood. This, again, mirrors the arguments made by the CEGB in contrast to the precautionary principle (Hajer 1995; see 2.2.1d): essentially, Science could find the answer, but it must be given more time, and a "forest effect" should be proved before management would change. It should be stressed that this is in advance of the precautionary principle's official inclusion in the Rio Declaration of 1992.

3.2.2b The first Edition

The first edition of the *Forest and Water Guidelines* was introduced as a policy response to external pressure on the Forestry Commission from the Water Research Council. As a result of significant publicised cases where sediment from poorly managed forest activities destroyed water treatment works (Crai/Homestyles reservoirs: see Stretton, 1984; Burt and Oldman, 1985; Stretton, 1997) a joint FC/WRC meeting was organised in York in 1986 (Solbé, 1986). Acidification, although raised at the meeting, was far from central to the debate. Nonetheless it is suggested in the report that avoiding planting in high, risk areas might be the best solution:

"*If the requirements of a potable supply are met, most other environmental problems will largely be resolved as well. Acidity could be the exception. In some cases it might be necessary to avoid areas sensitive to acidification rather than attempting to cure the resulting problems.*" (Solbé, 1986).

However, the final version of the first edition of the guidelines focused far more on sedimentation issues, and putting the advice of Mills (1980) into a more formal setting. Acidification was mentioned but the advice offered was minimal:

"*Means of overcoming the problems of acidification are still under investigation. No proven, long-term, solution exists at present. Where afforestation of conifers is proposed on poorly buffered soil the developer should consult the local water authority before detailed plans are submitted.*" (FC, 1988)

According to the Forestry Commission hydrologist: "*the reason [acidification] wasn't high up in the first edition of the guidelines is that there was quite a debate on the issue, some conflict - there was no agreed position in terms of what part forestry played in this*" (FCH).

3.2.3 *The "Forest Effect" in the academic literature*

Table 3-2 summarises the academic literature between 1980 and 1989 on the nature of the "Forest Effect" on freshwater acidification. Four major methodologies were applied to identify this working at two scales. The first three methodologies worked at the scale of paired catchments using either a) contemporary field data, b) long-term diatom-based pH reconstructions or c) long-term field data. The fourth approach worked at a regional scale, using a much wider database of collected data; the findings of these four methods are summarised below.

3.2.3a Paired catchment: Contemporary field data

These approaches (blue in Table 3-2) used contemporary field water chemistry/ecology data and compared these between a number of forest and moorland streams. To control for regional differences, streams were selected on similar geologies or sorted by the calcium/hardness/base cation content of the water samples (see "Control" in Table 3-2). These studies identified a "forest effect" in forest streams in terms of a lower pH and increased levels of sodium, chloride, sulphate and aluminium. Links with biology were also identified, with lower numbers of both fish catch and young fish recruitment identified in forest streams (Harriman and Morrison, 1982; Stoner and Gee, 1985). The links between chemistry and ecology are discussed in the following section.

3.2.3b Paired catchment: Long-term reconstruction (diatom-based)

These methodologies (yellow in Table 3-2) used sediment cores to construct diatom records that identified that the onset of acidification was a) prior to afforestation (Battarbee, 1984; Flower *et al.*, 1987) and b) exacerbated by afforestation in areas of high sulphate deposition (Kreiser *et al.*, 1990).

3.2.3c Paired catchment: Long-term comparison (field-data based)

Long-term datasets of measured water quality were rare (red in Table 3-2). Ormerod and Evans (1985) compared a three year average from 1967-1970 with a three year average 1983-1985 to show forest streams decreasing more rapidly in terms of pH than moorland streams. In Galloway a long-term study of forestry and acidification had been set up at Loch Dee in 1980 (section 4.4.1d(i)), Welsh and Burns (1987) report an increase in sodium ion concentration in the forest burn (Green Burn) during sea salt events, and link this to the Burn's comparatively lower pH during high rainfall events.

In addition to Loch Dee, long-term records comparisons were also available from Loch Ard in central Scotland and Llyn Brianne in mid Wales; Nisbet (1990) draws from the unpublished work at these sites to conclude "At both Loch Dee and Llyn Brianne, the results do not support the thesis of increasing acidity; either a) with increasing tree growth to canopy closure, or b) with continued growth during the initial post canopy closure phase".

Table 3-2 Forest Effect in the academic literature c.1989

Study	Type	Forestry	Control	Alt	pH	Na
Wright and Henriksen, 1979 Galloway, SW Scotland Streams: 11 (3F/4PF/3M)	PC C	<15*	Geology	<>300m	×	↑
	*No indication of forest age in text, Puhr (1997) calculates age from For					
	Type	Forestry	Control	Alt	pH	Na
Harriman and Morrison, 1981 Loch Ard, W Scotland Streams: 2 (1F/1M)	PC C	>24	Geology*	>300m	↓	↑
	*not specified					
	Type	Forestry	Control	Alt	pH	Na
Harriman and Morrison, 1982 Loch Ard, W Scotland Streams: 12 (7F/5M)	PC C	>24	Geology*	>300m	↓	↑
	* forest streams also had slightly lower calcium concentrations (c.50 vs. **Egg box studies show 2/12% survival in two forest streams in compar between pH and invertebrate biomass, suggesting scarcity of food is nc					
	Type	Forestry	Control	Alt	pH	Na
Stoner *et al.*, 1984 Tywi, Mid Wales Streams: 13 (7F/6M)	PC C	23	$CaCO_3$	>300m		
	Type	Forestry	Control	Alt	pH	Na
Stoner and Gee, 1985 Tywi, Mid Wales Streams: 2 (1F/1M) Lakes: 5 (3F/2M)	PC C	>13*	$CaCO_3$	>300m	↓0.5	↑
	*Streams with forest >24 years, Lakes with forest aged 13-43 years					
	Type	Forestry	Control	Alt	pH	Na
Reynolds *et al.*, 1986 Plynlimon, Mid Wales Streams: 5 (2F/3M)	PC C	>20	$CaCO_3$	>300m	*	
	*role of localised catchment geology factors stressed referring to the im in one of the study catchment. ** x2.5 at high flow; x3.1 at mean flow.					
	Type	Age	Control	Alt	pH	Na
Bull and Hall, 1986* Cumbria, NW England Streams: X (2F/XM)	PC C	30/47	?	>300m	×*	
	Type	Age	Control	Alt	pH	Na
Williams *et al.*, 1987 Dartmoor, SW England Stream: 1(F/M)*	PC C	55	Same River		×	
	*Compared pH between above and below forest; found no significant in					
	Type	Forestry	Control	Alt	pH	Na
Battarbee, 1984 Galloway, SW Scotland Lochs: 4 (3F/3M)	D PC LT			<>300m	×	
	Acidification predates afforestation "it can be concluded that afforestatic however, "it is impossible yet to ascertain whether forestry is an importa pre-afforestation ploughing distorts the sediment record."					
	Type	Forestry	Control	Alt	pH	Na
Flower *et al.*, 1987 Galloway, SW Scotland Lochs: 6 (3F/3M)	D PC LT	>30		<>300m	≈	
	*Explains that "the most likely cause of acidification" is acid deposition t Grannoch] has been exacerbated by afforestation".					
	Type	Age	Control	Alt	pH	Na
Kreiser *et al.*, 1990;Battarbee, 1989 Loch Ard & Loch Shiel areas, W Scotland Lochs: 2x 2(1F/1M) S:(0.8/1.2 kg ha-1 year-1)	D PC LT	Growth	Ca	≤100m	↓*	
	*Diatom reconstruction at Loch Chon showed pH fall from 5.8 to 5.2 foll Tinker nearby did not show this trend. The effect was not shown in the l					

Ormerod and Edwards, 1985
Plynlimon, Mid Wales
Streams: 6 (2M/4F)

Type	Forestry	Control	Alt	pH	Na
PC LT*	<48	$CaCO_3$	<>300m	↓x2.5*	

*decline in pH was 242% greater in forested catchments comparing 196

Welsh and Burns, 1987
Loch Dee, SW Scotland
Streams: 2(1F/1M)

Type	Forestry	Control	Alt	pH	Na
PC LT	≈13	Geology	<>300m		↑*

*afforested catchments reduction in proportion of base flow and greater during sea salt events" referencing Langan 1985. Conclusion: "at Loch increase in the acidity of surface waters"

Wright and Henriksen, 1979
Galloway, SW Scotland
Lochs: 72 (various %)

Type	Forestry	Control	Alt	pH	Na
R C	%(<15)*	Geology	<>300m	×	↑

*No indication of forest age in text, Puhr (1997) calculates age from For were below 15 years in age.
** Concluded: "effects of forestry are small relative to variation in other f

Harriman *et al.*, 1987
Galloway, SW Scotland
Lochs: 22
Streams: 27 (8F/8YF/11M)

Type	Forestry	Control	Alt	pH	Na
R* C	F/YF/M	Ca+Mg	<>300m	↓0.7**	

*Use regression analysis to show pH for any given Ca + Mg is higher fo
** at 60μeql^{-1} Ca+Mg, a forest stream is 0.7 pH units lower and 70 μeql
*** Chemistry (pH, Ca and Al) listed as key impact on fish health and sh
† a combination of forestry and acid deposition will acidify forest streams

Ormerod *et al.*, 1989
Streams: 113 (various %)

Type	Forestry	Control	Alt	pH	Na
R C	%	$CaCO_3$	<>300m	↓*	

*pH and aluminium separated by calcium classes showed significant (P
** Gee and Stoner, 1988 use the same data and find no significant relat

Type		Forestry:		Alt(itude):		pH/Na/Cl/xSO_4/Al:	
R	Regional Approach	%	Forest % used as variable	>300m	All sites over 300m	↓	Negative forest effe
PC	Paired Catchment	<X	X=Forest age	<>300m	Some sites under 300m	↑	Positive forest effec
C	Contemporary Data	F/YF/PF	Forest Y(oung) P(artial)			≈	Some/ unclear fores this variable
LT	Long-term data	M	Moorland			×	Forest effect non-ex

3.2.3d Regional Studies

Studies at a regional scale (green in Table 3-2) were introduced as sceptics of the "forest effect" questioned the comparability of paired catchment approaches (see section 3.2.4b). The regional approach assumed that by using a large enough database the effects of compounding factors, such as variations in soil type, geology and altitude could be reduced. Ormerod *et al.* (1989) demonstrated through regression analysis that statistically significant relationships existed between forest cover and both aluminium and pH for sites separated by calcium content for sites in Wales, a fact later reinforced for Galloway by Puhr *et al.* (2000).

3.2.4 Debate over the "Forest effect"

3.2.4a Forestry Commission vs. Welsh Water

In the absence of an agreed Forestry Commission position, and with no Forestry Commission guidance for acidification in place, the Welsh Water Authority were convinced of a "forest effect" by regional scale correlations between forestry and poor water quality in the Llyn Brianne area (Stoner *et al.*, 1984; Stoner and Gee, 1985). In response they set their own guidelines (Gee and Stoner, 1989) and "*during 1985 and 1986 they objected to any major forestry developments within the area on the basis that it would lead to a significant increase in water acidity*" (Nisbet, 1990a).

The Forestry Commission objected to this interpretation of scientific evidence and requested to re-analyse the data in collaboration with the WWA. The data showed a "*highly significant*" relationship between percentage forestry and both pH and aluminium. The Forestry Commission argued however that "*this relationship was of little practical significance*" since "*there was a great deal of scatter*" with the R^2 for pH was $\approx$0.11 and $\approx$ 0.3 for aluminium. They argued that a) the correlations were "*not proof of cause and effect*" b) that "*extrapolating of the data for the purpose of setting guidelines was invalid*" as the "*fitted regressions would be extremely unreliable*" due to the scatter, a fact they had validated by an independent statistician, c) that their justification on grounds of protecting fisheries was questionable as no significant relationship had been shown between forest cover and trout abundance referencing Stoner and Gee (1988) and d) that "*even if the relationship established in 1984 ... represented as real forest acidification effect, there is doubt to which this ... can be transferred to a point in the future when acid deposition levels are expected to be much lower*" (Nisbet, 1990a).

In essence, Welsh Water and the Forestry Commission were shown to have different tolerances in terms of the level of proof required for a precautionary approach to be justified. Furthermore, the Forestry Commission's arguments in the face of scientific evidence were that more certainty was required. Evidence of a relationship was not enough; management actions needed to be shown to be effective, and effective over the long-term before guidance could be set.

3.2.4b Forestry Commission vs. Acid Waters Review Group

In 1988 the Acid Water Review Group, a body of experts set up to report to the Department of the Environment on the impacts of acidification in the UK submitted a report to the DoE that in the eyes of the Forestry Commission placed "*a strong emphasis on the role of conifer afforestation as a direct cause of surface water acidification*" (Nisbet, 1990b).

The AWRG report had done just that, referencing the paired catchment work shown in Table 3-2:

"There is evidence from Wales (Stoner and Gee, 1985; Reynolds et al, 1986), the Lake District (Bull and Hall, 1986), and Central Scotland (Harriman and Morrison, 1982) that streams of similar sensitivity (calcium content) draining forestry plantations are more acid and/or contain higher concentrations of aluminium than streams draining grassland or moorland" (AWRG, 1988; references included).

They stress that the "forest effect" is not found in all forest streams; it is most clear on sites "*with high sulphate deposition and naturally acidic, poorly buffered waters.*" particularly thin/acid soils over bedrocks poor in base cations, or slow to weather and release them. The AWRG also reference the work of Reynolds *et al.* (1986) where a "forest effect" in terms of acid waters and high aluminium concentrations was shown as being possible "*even in some catchments with relatively high pH groundwaters ... during high flows (Reynolds et al. 1986)*" (AWRG, 1988, reference in original). The Forestry Commission strongly objected to these views and published a rebuttal of the AWRG report in their own bulletin series (Nisbet, 1990b) again stressing the scientific uncertainty surrounding the "forest effect": "*the evidence for the significance and scale of a forest effect is by no means as clear and conclusive as the report suggests.*"

In response, the Commission drew on further evidence from the academic literature and reference the diatom work of Battarbee *et al.* (1988) and Flower *et al.* (1987), to indicate that that a) acid deposition is the cause of acidification and b) that acidification at Loch Grannoch was shown to have begun before afforestation began. They stress that Galloway and mid/north Wales are both particularly susceptible locations and stresses that in these areas "*many lakes, regardless of whether their catchments are under moorland or forest, have been acidified below pH 5.0 and are now virtually fishless (Battarbee et al., 1988; Maitland et al., 1987)*" (emphasis and references in original). Finally they reference the work of Battarbee (1989) to argue that "*surface water acidification does not appear to be a problem in forested catchments within susceptible areas where there are only low levels of pollutant deposition*" (Nisbet, 1990b).

Having clarified its position the FC then lists the evidence from paired catchment studies that the AWRG used as evidence of a forest effect before dismissing a paired catchment methodology as fundamentally flawed:

"*The basic assumption in all [the listed] studies of paired catchments is that susceptibility of the underlying soils and geology to acidification is similar in the catchments compared, so that any difference in water quality can be ascribed solely to the effects of land use. In reality it is not often possible to find such comparability because of the variability of soils, geology and topography and the possibility of associations between the presence or absence of forestry and particular site conditions which influence land use. Consequently, the basic assumption of comparability between paired catchments is questionable*" (Nisbet, 1990b)

Some of the paired catchment approaches had used calcium/hardness as a means of separating catchments in terms of acid sensitivity but the FC (Nisbet, 1990b) stresses that "*there is some uncertainty over the extent that calcium concentrations alone can account for the range of factors that determine catchment sensitivity to acidification*" they stress that variations in pollutant inputs need to taken into consideration before determining a forest effect.

To reinforce its position, the Forestry Commission refer to the evidence from regional studies, sediment core studies, clear felling studies and long-term studies. In each case they stress the need for more research: the long-term studies have yet to show any evidence of a "forest effect"; the sediment core studies show inconclusive results; the regional studies whilst showing a relationship with pH show none with fish; and that the increase in aluminium shown four years after clear felling may be a delayed response to site disturbance.

They conclude: "*firm conclusions regarding the extent of any forest acidification effect can only be based on the analysis of results from the long-term studies which are currently being carried out*" (Nisbet, 1990b). As a result, the Forestry Commission preferred to delay changes to forest management until the time when "firm conclusions" could be made. It is clear, that the Forestry Commission were, at this time, far more selective in terms of the level of scientific proof needed to demonstrate a "forest effect" than either the AWMN or the WWA. By taking this hard-line realist/scientific approach (for whatever reasons) and dismissing many sources of knowledge insufficiently robust they restricted the forms of knowledge that could influence policy to a limited selection of long-term studies.

3.2.5 The "Forest effect" Agreed

3.2.5a Darlington 1990: Scavenging accepted as the "Forest effect".

As a means of resolving the ongoing debate between the Forestry Commission and the Acid Waters Review Group a joint FC/DoE meeting was arranged in June 1990 in Darlington. This meeting put the "forest effect" as the focus for both academic experts (the AWRG) and the Forestry Commission and allowed a consensus to be attained over the nature of the "forest effect".

The conclusion of the meeting was that, of the six mechanisms presented (see section 3.2.5), "*only forest scavenging of atmospheric pollutants appears sufficiently potentially significant to explain the effects which have been identified in some studies. The apparent importance of this indirect mechanism and the much smaller scale of [the remaining mechanisms] both in magnitude of effects and in potential land area affected*" (Forestry Commission and Department of the Environment, 1990).

This agreement on "*the indirect scavenging of pollution*" as the mechanism for the "forest effect" "*brought the consensus so quickly*" that the *Forest and Water Guidelines* were quickly reviewed and a second edition of guidance put into place (FCH). In 1991 the second edition of the *Forest and Water Guidelines* were published.

From a Network Theory and discourse coalition forming viewpoint (Hajer 1995; section 2.2.1e) the Darlington meeting was important as for the Forestry Commission it succeeded in ensuring that the hegemonic discourse[10] surrounding the "forest effect" was moved away from a "forest effect" *per se.* to a discourse focused on a "forest effect" of sulphate scavenging. In doing so, alternative "forest effects" (discussed in

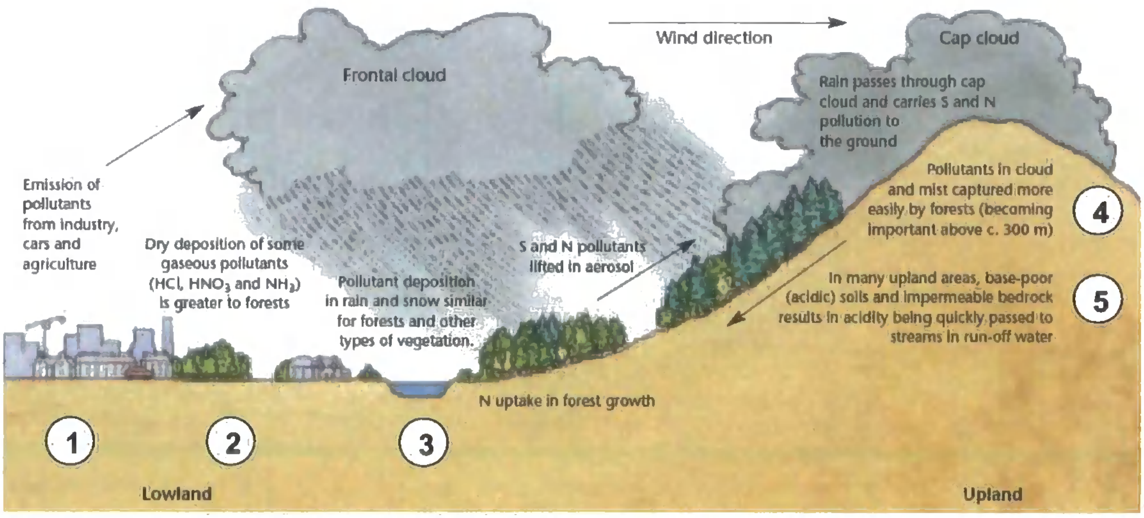
[10] Hegemonic discourse: the prevalent way in which the "forest effect" is discussed.

3.2.5d) were removed from consideration as ways in which the "forest effect" could take place, certainly from a policy response viewpoint. Instead, the policy responses to date have focused on risk-based approaches drawing on scientific understandings of the forest *scavenging of sulphate* mechanism.

3.2.5b The Scavenging Mechanism

Figure 3-1 shows diagrammatically the scavenging mechanism adopted as the "forest effect" in the second edition of the guidelines. The mechanism is explained in the bullet points below using quotations extracted from the Guidelines themselves to explain the key points as presented by the Forestry Commission by the Guidelines. The diagram and quotations are both from the fourth edition, but the details of the mechanism used have not changed from its introduction in 1991.

Figure 3-1 Interactions between forests and acid deposition (from Forestry Commission, 2003b)



- "The primary cause of acidification is the deposition of acidifying sulphur and nitrogen compounds from the atmosphere" (1)
- "The quantity of sulphur and nitrogen pollutants deposited at a site is strongly influenced by the nature of the vegetation layer. Forest canopies can significantly increase the capture of some of these pollutants." (2-4)
- There are three mechanisms by which pollutant can be deposited, dry (2), wet (3) and occult (cloud/ mist) deposition (4)
- "Increased capture ... is a function of stand structure. The effect therefore becomes more important as trees grow" this applies in terms of both dry (2) and occult (4) deposition; wet deposition (3) is not affected by forestry.

- "The enhanced capture of mist (4), which can contain large concentrations of sulphur and nitrogen, is greatest at high altitude because of the increased duration of cloud cover and high wind speeds"
- "Acidification of freshwaters occurs when the input of these pollutants exceed the buffering capacity of the soil and rocks through which the water passes." (5)

(Forestry Commission, 2003b)

3.2.5c The science behind the scavenging mechanism

The science behind the scavenging mechanism is summarised in Fowler et al. (1989) which collated existing knowledge on the deposition rates to forestry of a variety of potential pollutants to determine the total contribution of forestry to pollutant deposition. Fowler et al. (1989) focussed on the three mechanisms of deposition (C. in list above) and calculated the differences to the contribution of each to a variety of ions (Table 3-3) using an example of Kielder forest in North East England. The work showed that forests increased the scavenging of nitrogen and sulphur from the atmosphere by 89% and 30% respectively (Table 3-3).

Table 3-3 The forest scavenging effect (modified from Fowler et al., 1989)

		Wet		Dry		Occult		Total	
SO_4^-	F	1.31		0.31		0.65		2.27	
SO_4^-	M	1.31	+0%	0.31	+0%	0.13	+400%	1.75	+30%
NO_3^-	F	0.35		0.42		0.09		0.86	
NO_3^-	M	0.35	+0%	0.22	+91%	0.02	+350%	0.59	+46%
NH_4^+	F	0.45		0.93		0.1		1.48	
NH_4^+	M	0.45	+0%	0.18	+417%	0.02	+400%	0.65	+128%
N*	F	0.80		1.35		0.19		2.34	
N*	M	0.80	+0%	0.40		0.04		1.24	+89%
Cl^-	F	4.98		0.20		0.86		6.04	
Cl^-	M	4.98	+0%	0.04	+400%	0.17	+406%	5.19	+16%
Na^+	F	2.81				0.46		3.27	
Na^+	M	2.81	+0%			0.09	+411%	2.9	+13%
Mg^{2+}	F	0.33				0.04		0.37	
Mg^{2+}	M	0.33	+0%			0.01	+300%	0.34	+9%
Ca^{2+}	F	0.62				0.07		0.69	
Ca^{2+}	M	0.62	+0%			0.01	+600%	0.63	+10%
*Calculated from NO_3^- + NH_3^+; F= Forest M= Moorland									

Another key aspect introduced by Fowler et al. (1989) was the importance of "occult deposition" from the cloud layer, which was shown to be considerably different between forest canopies and moorland, particularly in terms of sulphate. Cloud particles (5-

40μm) are considerably larger than dry particles (0.1-5μm), and as a result are collected far more efficiently by foliage via impaction and sedimentation. As a result, when dry pollutant particles become the nuclei for cloud droplets they increase in their ease of pollutant transfer to the forest canopy.

Fowler et al. (1989) stressed the implications of this in terms of forestry stressing that that *"forests that are frequently enveloped in cloud associated with wind speeds of 5-10ms^{-1}"* which the paper links to "*much of the land in western Britain at altitudes in excess of 400m*" are likely to receive additional cloud water pollutant inputs equal to around 10% of the precipitation input. For areas over 600m "*which are in cloud for typically 2000h/year ... cloud water deposition may increase precipitation by about 12% and may add up to 40% additional solutes to wet deposition*" and effect that is "*much less important over shorter vegetation*".

In recognition of the scavenging effect, the importance of occult deposition and the link between forestry, altitude and cloud cover the Forestry Commission integrated new rules into the second edition *Forest and Water Guidelines*. This rule recognised, referencing Fowler et al. (1989), that "*i) elevation >300m ii) percentage forest cover, forest age and iii) frequency of cloud cover and gradients with altitude*" were the key factors affecting the forest impact on acidification. It was deemed that any new planting of over 10% forestry should be limed: providing that the planting was in a sensitive area (see section 3.2.6a); the method by which this was identified is discussed in section 3.2.5e below.

3.2.5d Other Forest Effects

It is worth noting that the Darlington meeting was far from the first time that forest scavenging had been recognised as the most probable cause of acidification, diatom studies had suggested as much since 1987 (Flower *et al.*, 1987; Battarbee *et al.*, 1989). Miller (1988) performed a similar review of potential "forest effects" at the Edinburgh conference "Acidification in Scotland" in November 1988 came to the same conclusion "*the most convincing explanation must be the potential of forests in polluted regions to exacerbate the rate of transfer from atmosphere to soil*". Furthermore the Forestry Commission itself was arguing along a very similar vein in Nisbet (1990) "*there is evidence for an association between forested catchments within acid sensitive areas receiving high levels of pollutant deposition and stream waters with higher acidity, this cannot be taken as proof of acidity* per se."

As discussed in section 3.2.5a for the Forestry Commission the key result of the Darlington meeting was the agreement of scavenging as the agreed "forest effect", and the only "forest effect" that a FC policy response needed to address. This effectively eliminated the other five potential "forest effects" discussed at the meeting from consideration during the land management process. The extent to which this dismissal is a factor that that has impacted the ability of policy and practice to address the "forest effect" will depend on whether or not these alternative mechanisms play an influential role in areas where policy does not already apply. As, with climate change and a reduction in sulphate emissions, the relative importance of some of these mechanisms may well have changed they are considered below along with the logic behind their exclusion from the *Forest and Water Guidelines*.

3.2.5d(i) Drying of Soils

Forest growth to canopy closure, as well as forest practices of ploughing and draining can contribute to the drying of soils. This, in turn, results in the oxidation of sulphur and nitrogen compounds and can release acidity. Furthermore in organic soil horizons drying increases cation exchange capacity and reduces base saturation. However these mechanisms are not thought to be a likely *cause* of freshwater acidification, and were discounted at the Darlington meeting, as the oxidation effect was seen to be "*localised and short lived*" and the cation exchange effect was seen to be "*negligible*" in the absence of mobile anion inputs (Forestry Commission and Department of the Environment, 1990).

3.2.5d(ii) Litter Decomposition

Conifer forests, when planted on acid soils, produce "*an acid surface organic layer which increases the total acidity of the soil*" (FC and DoE, 1990). The impact of this is dependant on the flow through these surface layers, as if the water percolates through a mineral soil, the organic acids will be broken down or precipitated and the runoff will not be acidified (FC and DoE, 1990). It was accepted that direct run off from these surface layers would be acidic, but would not contain toxic aluminium and concluded that "*this mechanism does not therefore explain acidification of surface waters or biological effects in general, but it may apply in some special situations.*" (FC and DoE, 1990)

3.2.5d(iii) Base Cation Uptake

Trees absorb uptake base cations from the soil into the tree biomass; when trees are felled and removed as timber this loss is made permanent. In the absence of sufficient weathering the preferential removal of cations can lead to an acidic imbalance in the soil; as such, the impact of this effect depends on the supply of base cations within the soil (Whitehead *et al.*, 1988). This effect was thought at the meeting to be slow, taking around 20 years to become apparent, and impacts on drainage water are thought to be "*small in the absence of atmospheric pollution*" and "*unlikely to produce substantial changes in aquatic biota*" (FC and DoE, 1990). It should be noted that base cation uptake, whilst not prioritised at the meeting as needing prescribed management, is a recognised "forest effect" in model-based approaches such as MAGIC (Cosby *et al.*, 1985; Neal *et al.*, 1986; Whitehead and Neal, 1987; Whitehead *et al.*, 1988; Jenkins *et al.*, 1990). In 2003, it remains recognised by the Forest and Water Guidelines as "*not fully understood*" and needing further research (FC, 2003), although there are no prescribed impacts on land management that result from this recognition.

3.2.5d(iv) Increased Evaporation

After canopy closure is achieved increased evaporation from the canopy layer is estimated to reduce catchment runoff by around 2% for every 10% of the catchment afforested. This process leads both to a concentration of soil waters and a modification of soil-solution interactions; on acid soils increased mobilisation of aluminium rather than base cations can result. Pollutant deposition will determine the impact of this on drainage waters; in the absence of pollutants the impact is seen to be negligible (FC and DoE, 1990).

3.2.5d(v) Altered water pathways

Forest ploughing and root development allow waters access to deeper soil horizons. The impact of this on acidity depends on the soil, but in general is thought to allow waters a longer retention time within the soil, encouraging neutralisation by base cations and reducing acidity and flashy responses to storm rains (FC and DoE, 1990).

3.2.5e Introducing the Critical Loads approach

Whilst the acceptance of scavenging and the role of occult deposition led to recognition that special care should be taken in high-altitude forests in acid sensitive areas, a mechanism was needed to identify which areas were sensitive. It was decided at the Darlington meeting that the Critical Loads approach, under development at that time, provided a method by which the Forestry Commission could identify sites in need of sensitive management.

The concept of the critical load had been adapted by Scandinavian scientists for use as a policy tool for ECE CLRTAP (Nilsson and Greenwelt, 1988) based on the underlying concept is that acidification is a "*large scale titration*" (Henriksen, 1980); that extra acid inputs from the atmosphere can tip the balance between an acidified and a non-acidified system. The critical load is the maximum load of acid input a site can take, due to its own buffering capacity, before harmful impacts can be expected. The most common official definition of **a critical load** is *"a quantitative estimate of exposure to one or more pollutants below which harmful effects on specified sensitive elements of the environment do not apply to present knowledge"* (Nilsson and Greenwelt, 1988). Critical **load exceedance** is therefore the result of subtracting the critical load from pollutant deposition with any cases where the deposition is greater, and thus yielding positive results indicating that there is a likelihood of damage to the selected sensitive elements. It is important in terms of terminology to ensure that the difference between the **critical load** and **critical load *exceedance*** is well understood.

The definition of critical load is defined to be flexible so that it can be adapted to a variety of potential a) pollutant inputs b) sensitive elements of the environment and c) methods for estimating exposure. In the UK, a Critical Loads Advisory Group (CLAG) was set up in the early 1990s following the UK's signing up to UN-ECE CLRTAP (section 1.2.1a) and this applied a series of models to create Critical Loads sensitivity maps of both nitrogen and sulphur deposition on vegetation, soils and freshwaters using a variety of methodologies that have changed with time (see Hornung and Skeffington, 1993; Centre for Ecology and Hydrology, 2003).

At the time of the Darlington meeting the CLAG was in the process of preparing "Critical and Target Load Maps for the United Kingdom" (Department of the Environment, 1991, 1992) identifying the 10x10 km squares in which freshwaters would not be protected in the year 2005. It was these squares that the Forestry Commission used to form the basis of forestry guidance within the second edition of the guidelines.

3.2.6 The "forest effect" into practice: 2^nd^ and 3^rd^ edition guidance

The guidance in the 2nd edition of the *Forest and Water Guidelines* can be summarised as follows:

1) Is the area a new planting?
2) Is the area in a Critical Loads exceedance square?
3) Will the planting result in over 10% of the catchment area above 300m to be planted?
4) If "Yes" to all, *"powdered limestone should be applied except where conservation considerations are important"* (Forestry Commission, 1991)

It represents the acceptance by the Forestry Commission that a) the Critical Loads model is a sufficient mechanism for identifying areas at risk from acidification and b) that increased occult deposition is the major cause of the "forest effect" and that this is unlikely to have an impact below 300m. Its solution for sensitive management is to continue planting, but to lime the soil to counteract the enhanced acid loading.

The 1991 Guidelines were only in place for two years. In 1993, reflecting "*a move away from liming*" (FCH), the *Forest and Water Guidelines* were revised into their third edition. This lasted until 2004, with only a minor update in 2000 to add "administrative detail" (FCH).

The approach in the third edition was:

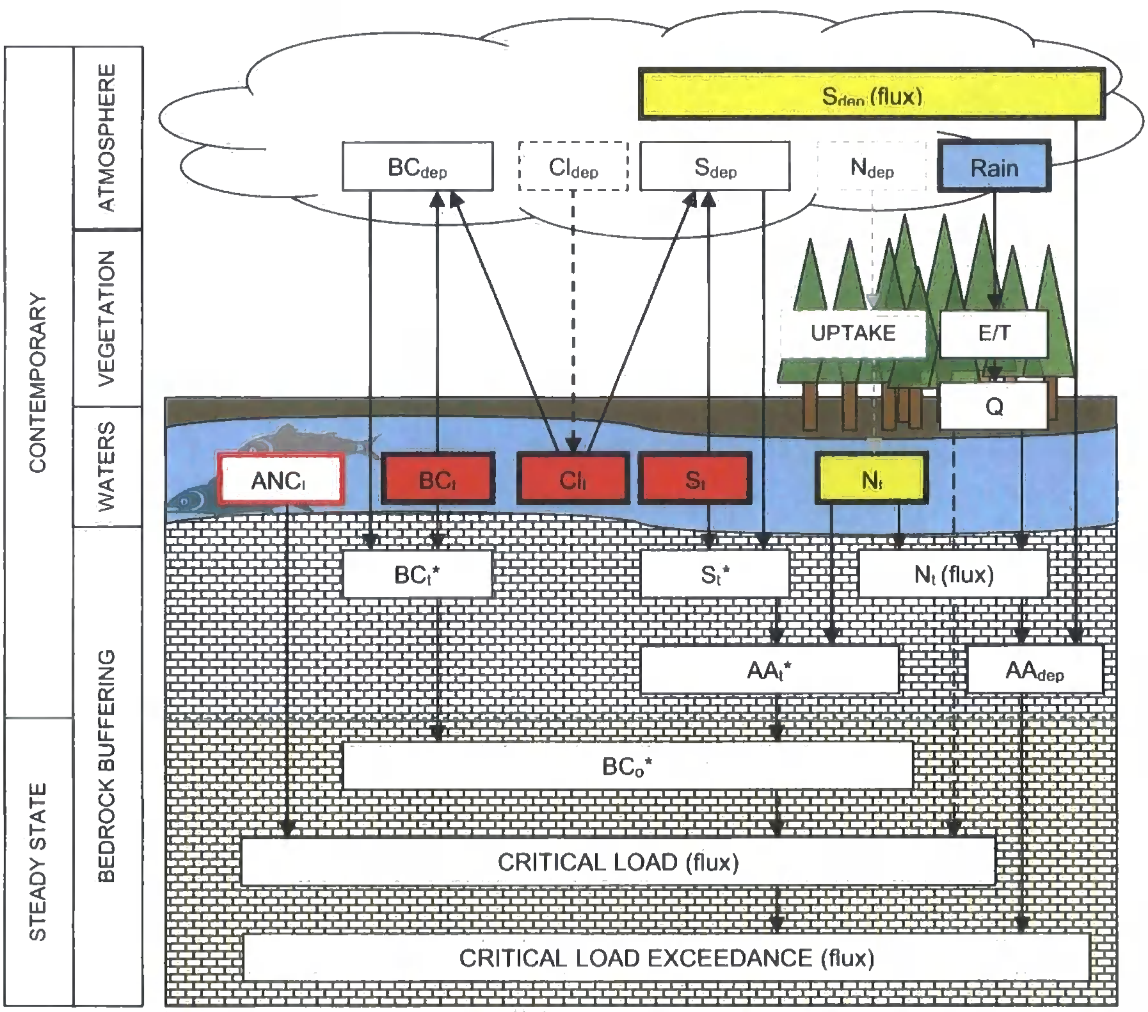
- Is the area a new planting?
- Does the site fail a catchment-based critical load test?
- Is the area in a Critical Loads exceedance square?
- If "Yes" to all, then "*the approval of a Woodland Grant Scheme is unlikely until there are further reductions of pollutant emissions or unless ameliorative treatments are applied without detriment to the ecosystem.*" (Forestry Commission, 1993)

3.2.6a Catchment-based Critical Loads

The significant change was a move away from the 300m rule towards performing Critical Loads exceedance tests at a catchment scale. The reasons for the selection of the Critical Loads model were explained to be that it was a) a simple approach that can easily be applied "*there are other models available dynamic models, other steady state models, from the point of view of simplicity and ease of application this is the one that we have selected and is seen as being best*" (FCH) b) that it is an approach takes ecological sensitivity into a chemical model "*the strength of this approach is that we are relating the deposition, the pollutant pressure to a sensitive element of the biology*" through its use of the ANC_{LIMIT} around which "*there is little question that ANC is a good conservative chemical criteria to use as the foundation for assessing biological response*" and for which, "*there is a lot of data out there in terms of establishing these response relationships*" and c) that the approach takes acid deposition into consideration. It is this final point that is the key difference between this and other field collected measures, a point which forms the cornerstone of their argument for the application of the approach: the Critical Loads approach provided a way to "*quantify the susceptibility of a given catchment ... to quantify what part forestry plays in terms of scavenging ... and put both of these together to work out whether a proposal is contributing to acidification or not*" (FCH).

As discussed in section 3.2.5e there is more than one Critical Loads model. The Forestry Commission selected to follow the Steady State Water Chemistry (SSWC) model adopted by the national CLAG freshwaters subgroup. This methodology was first introduced by Nilsson and Grennfelt (1988) and is outlined in detail in Henriksen and Posch (2001) and Appendix A; Figure 3-2 shows an overview of the method, and a simple summary is given below.

Figure 3-2 The SSWC Critical Loads model.
Diagram based on text of Nilsson and Grennfelt (1988)



BC	Base Cations	Cl	Chloride	E/T	Evapotranspiration
N	Nitrate	S	Sulphate	ANC	Acid Neutralising Capacity
Q	Discharge	AA	Acid Anions	L	Limit
dep	Deposition	t	Contemporary	o	Steady-state
	Input variable		User-selected	*	Corrected for sea salt

3.2.6a(i) Input data

The SSWC Critical Loads model is ideal for the Forestry Commission's purposes as it requires relatively little input data, and the required data are easy to obtain. The mandatory input variables are shown with a thick black border in Figure 3-2 and are:

i) catchment sulphur deposition (S_{dep}), extracted from national maps produced by CEH;

ii) a catchment rainfall figure (Rain) or direct information on runoff (Q);

iii) data from a water sample taken from the catchment including standard anions (S_t Cl_t and N_t) and cations (BC_t).

3.2.6a(ii) Critical Loads Exceedance

Critical Loads *exceedance* is calculated as the difference between the acid anions deposited in the site (AA_{dep}) and the site's critical load (Nilsson and Grennfelt, 1988).

3.2.6a(iii) Critical Load

The **critical load** at the site is equal to the original base cations (BC_o) plus an ANC limit (ANC_L) selected by the user as a margin below the equilibrium between acid anions (AA_{dep}) and base cations (BC_o) required to meet the ecological targets to which the model is put (Nilsson and Grennfelt, 1988).

3.2.6a(iv) Sea Salt Correction of Base Cations and Sulphate

A large part of the complexity in Figure 3-2 is a result of the process of sea salt correction. The SSWC model uses base cations that derive from the catchment; unfortunately atmospheric sea salt deposition brings with it added inputs of cations and sulphate. It is necessary to remove these from the model. This is achieved by assuming that all chloride detected in the water sample originates from sea salt. With this assumption, the sea salt deposition of cations (BC_{dep}) and sulphate (S_{dep}) can be calculated by their known ratios with chloride in sea-water (see Appendix A). By subtracting the deposited proportion from that found in the water sample, a sea salt corrected proportion can be identified (i.e. $X_t - X_{dep} = X_t^*$) (Nilsson and Grennfelt, 1988).

3.2.6a(v) Original Base Cations

With sea salt removed, BC_o^* can be calculated from sea salt corrected contemporary base cations (BC_t^*), nitrate (N_t^*) and sulphate (S_t^*) concentrations taken from the contemporary water sample (see Appendix A for detail). This is far from simple and involves the use of an F-Factor that relates constants drawn from Scandinavian data to predict the relationship between contemporary and original anion and cation levels. Different studies have derived different constants, leaving choice of parameters up to the model user to decide. Both the CLAG and Forestry Commission use constants from Brakke *et al.* (1989).

3.2.6a(vi) Deposited Acid Anions

AA_{dep} is calculated as the Sulphate deposition (S_{dep} (flux) in keq ha^{-1} year^{-1}) plus the contemporary nitrate in the water sample converted into the same unit (keq ha^{-1} year^{-1}). This is done using catchment rainfall. It is assumed that 85% of rainfall becomes discharge and the remaining 15% is removed by evaporation and transpiration. Measured nitrate is used as it is assumed that uptake by vegetation will consume a large proportion of deposited nitrate. Thus, only the proportion that makes its way into the water sample is likely to be contributing to acidification (Nilsson and Grennfelt, 1988).

3.2.6a(vii)The choice of ANC limit

The choice of ANC limit is the In addition a decision also needs to be made regarding the critical limit of ANC to set in order to protect the preferred sensitive organism (ANC_L, boxed in red in Figure 3-2). The Forestry Commission, following CLAG, selected a critical ANC value of zero. This value is set drawing on the work of Henriksen, and shown by Lien *et al.* (1996) to be a condition at which there is a 50% chance of damage to brown trout populations, but a 0% chance of extinction. It should be noted that whilst the FC have kept ANC_L at zero the UK national Critical Loads exceedance maps generated by CEH now use a ANC_L value of 20 (Hall *et al.*, 2004). The Forestry Commission justify this decision as they use a high-flow worst-case sample rather than one from median flow; this is discussed in 7.2.2a(ii).

3.2.6b Restocking

It is important to recognise that the guidance described in the second and third editions of the *Forest and Water Guidelines* only applied to new plantings. Restocking of previously planted land could continue without need for checks, in fact this was stipulated under the conditions of Woodland Grant Schemes. This proved to be a major source of contention at the regional scale (as discussed in section 3.3.4a).

3.3 Forest and Water Guidelines Versions 1-3 in practice

3.3.1 Introduction

The previous section illustrated the history of the debate over the "forest effect", the way airborne pollutant scavenging came to be the accepted "forest effect" and the method by which it is interpreted in the *Forest and Water Guidelines* editions 1-3. The following section refers to stakeholder interviews, and a worked example of Galloway forest district to evaluate the extent to which the *Forest and Water Guidelines* helped tackle the issues of acidification within the region.

3.3.2 The Forest and Water Guidelines; a good idea in principle

Overall, the *Forest and Water Guidelines* are recognised by most stakeholders to have made a significant difference to the management of the water environment (GFT, SEPA-G, SEPA-WFD*). The Forestry Commission's attitude is shown to have changed significantly particularly in terms of its attitude to soil erosion, drainage and planting in relation to watercourses. In a SEPA report focusing on forestry water quality issues in the South West of Scotland, Tervet and Coy (2002) state that "*much less concern is now expressed about soil erosion*" a fact which they attribute in part to *"the improved specifications and methodologies described in the Forest and Water Guidelines"*. They demonstrate that in spite of this evidence of bad practice continues and refer to SEPA's log of pollution-related events in SW Scotland to highlight 35 incidents between 1989 and 2000 where suspended sediment issues were linked to forestry practices. They are keen to stress however that "*the greater willingness of foresters and contractors to follow good practice and the increased likelihood of water regulators initiating a prosecution, have led to ... a general view that [drainage related sedimentation] is no longer the problem that it was*" (Tervet and Coy, 2002).

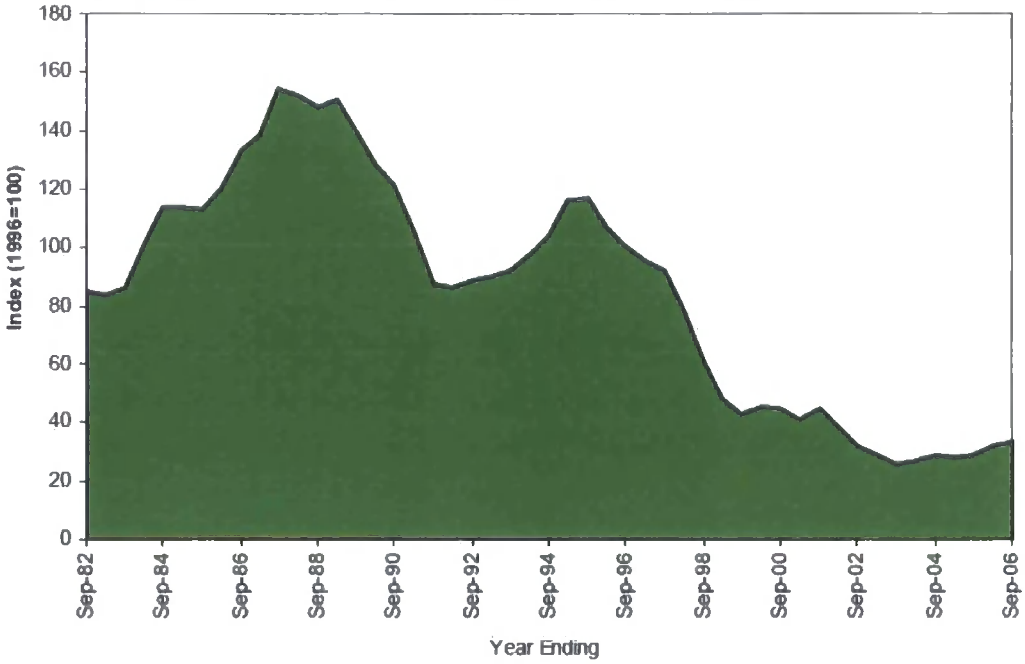
This view is also supported by the Galloway Fisheries Trust both at the time of their introduction; "*The Forest and Water Guidelines are really a tremendous step forward (apart from the acidification section) and old style forestry practice is on the way out. Problems still occur and will continue to occur because of the nature of the activity and because it takes place in unstable climatic conditions, but at least some of the worst examples of environmental mismanagement are hopefully a thing of the past*" (Stephen, 1994b) and today; "*their impact was very very slight to start off with, but even pulling back 5m from the water courses was unheard of at the start*" , the guidelines are now "*very good – they recognise the problem*" (GFT).

3.3.3 A changing Forestry Commission

It should be noted at this point that the *Forest and Water Guidelines* were not the only factor affecting the change in attitude between forestry and the water environment, and that with the formation of Forest Enterprise in 1992 there was a significant shift in the outlook of the Forestry Commission, and a change in role from timber production to one of mixed value forestry with increased importance placed on both environmental and recreational roles provided by forest sector. A brief summary of this follows.

3.3.3a Pre-1988: Timber Reserves

Figure 3-3 Coniferous Standing Sales Price Index for Great Britain (year ending Sept 1996=100, real terms; from Forestry Commission, 2006c)



In addition to changes in terms of the policy applied to water quality it is important to recognise changes within the Forestry Commission as a whole.

Between 1978 and 1991, the role of the Forestry Commission's targets were set by the 1967 Forestry Act: "*promoting the interests of forestry, the development of afforestation and the production and supply of timber and other forest products in Great Britain.*" The origins of this approach stemmed from the First World War where disruption of overseas timber supplies led to a heavy reliance on native timber and significantly reduced UK timber reserves. The Forestry Commission was set up to ensure a strategic three year wood reserve in the event of another war. Although the advent of modern warfare changed motivation for afforestation from defensive reserves to capital returns (Oosthoek, 2000), the overall impact was very similar and the wood industry became a "*factory [that] needs to be fed by raw materials mass produced in the forests*" (Ryle, 1961).

Timber prices were high relative to today's (Figure 3-3) and the 1967 Forestry Act encouraged the forestry sector both through subsidy the creation of mills and chipboard plants as well as tax incentives for plantation. To maximise capital gains fast-growing species were preferred, and large areas of land were rapidly afforested so that, by 1980, Scotland had managed to double its forest cover, from 5.6% in 1924 to 11.8% (Scottish Natural Heritage, 2004).

It should be noted, however, that, whilst forestry's drive at this time was definitely focused on timber production, the introduction of the Countryside Act of 1968 gave the FC the additional responsibility to "*have regard to the desirability of conserving the natural beauty and amenity of the countryside*" and provided them with powers for the provision of recreational facilities and planting for amenity purposes (National Digital Archive of Datasets, 2000). In addition the 1986 Broadleaves act introduced a new focus on expanding planting beyond coniferous species and increased incentives for afforestation with broadleaves.

3.3.3b 1988: Forestry vs. the Environment: the Flow Country Debacle

During the 1980s the Forestry Commission found itself in the position of "*antagonist to the conservation communities*" (FC-G) due to increasing concern over blanket afforestation and the impacts of the tax incentives for forestry on the wildlife in sensitive areas. Key amongst these, in terms of changing policy and shaping the aims and objectives of the Forestry Commission post 1991 was the 1986-88 "Flow Country Debacle".

The Flow Country in Northern Scotland is an expansive area of peat land which provides significant amounts of unique bird habitat within the UK. During the period 1979-1985 Fountain Forestry, a private forestry company, encouraged by tax incentives and the low cost of agriculturally unprofitable peatland, bought up and transformed 40,000 hectares of the Flow Country with Sitka spruce. The Royal Society for the Protection of Birds (RSPB) became aware and raised the alarm, which in turn lead to the Nature Conservancy Council publishing a report "Birds, Bogs and Forestry" (Nature Conservancy Council, 1986) in which it criticised the forest industry. In the Finance Act of 1988 tax incentives for forest planting were dropped to be replaced by the current woodland grant schemes which provided increased incentives for the plantation of deciduous woodland.

This change put the Forestry Commission in a state of flux requiring "*a period of adjustment*" (Forestry Commission Annual Report 1988, Oosthoek, 2005) during which it continued to sell off significant parts of its estate to the private sector.

3.3.3c 1992: Forest Enterprise

In 1992 the Forestry Commission was internally restructured into two main divisions: "Forest Enterprise", tasked with the management of the Forestry Commission's estate and commercial activities and the "Forest Authority" which upheld the regulatory and policy advisory roles of the old Commission. Forest Research, the separate research branch of the old FC remained as a third division[11]. At this same time the UK government was making commitments at both the 1992 United Nations Conference on Environment and Development in Rio, and the 1993 Ministerial conference on the protection of European Forests in Helsinki. This led to "*sustainable forestry*" becoming the "*watchword*" for Forest Enterprise (Nisbet, 2004).

The change in role that came with the introduction of Forest Enterprise in 1992 is very much recognised by the Galloway Forest District Manager: "*Forest Enterprise was set up primarily with the aim of getting timber production right, but they still had the mandate for conservation, recreation and heritage and were happy with it. That was the real clincher 1992; there was a sudden realisation [during] the formation of [Forest Enterprise] of the fact that timber production was only a part of what we were doing.*" (FC-G)

A further key turning point in the history of the Forestry Commission's approach to the environment was the introduction of the Forestry Strategy in England in 1998 (Forestry Authority, 1998; FC-G). The Scottish Forestry Strategy (Forestry Commission, 2000) introduces the multiple values of forestry into forestry policy: *sustainability* is introduced as the strategy's "overarching principle" with four key guiding principles of integration, positive value, community support and diversity and local distinctiveness encouraging, amongst other factors, "*integration ... with other rural activities such as agriculture, conservation ... fisheries, recreation and tourism*" and that "*forests and woodlands should be managed in ways that enjoy public support. Complete agreement might not always be possible, but there should always be mechanisms for participation... and for working towards consensus*" (FC, 2000). In 2006 this was updated and now includes a recognition of a need to follow the precautionary principle by "*basing decisions on sound scientific evidence, while taking in to account scientific uncertainty (through the precautionary principle), as well as public attitudes and values*" (Forestry Commission, 2006b).

The extent to which the integration of sustainability and the recognition of multiple values of forestry are the driving reasons for the change in the Forestry Commission's attitude is a matter of some debate: some stakeholders (GFT-S, SEPA-G) attribute the Forestry Commission's attitude change to a decline in timber prices.

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[11] In this thesis differences between these divisions are not a focus of debate, as Forest Research's science and the Forest Authority's policy guide the actions of Forest Enterprise (Scotland); for the sake of simplicity this thesis talks discusses the "Forestry Commission" as a whole, and any differences specific to one division or devolved body are specified.

"*I think the change in attitude has been brought about by the price of timber. They're not making any money on timber at the moment; if they're breaking even they're doing well and that changes the emphasis: 'If we can't make money from it then what can we do?' 'Lets try and get some environmental credits out of forestry'*" (SEPA-G)

The FC District Manager in Galloway is quick to stress that timber prices were less significant in terms of the FC's changing attitude as was the change in the perception of the FC's role within the Forestry Commission; his views are to some extent supported by the timber price index shown in Figure 3-3 which indicate the that timber prices really only drop after 1997.

"*Although the timber prices were very good at that time (1992) it was recognised that in a high value economy like Britain we don't need to be growing commodities for commodities' sake; we have to be aware of the cultural and social values – and hence there was a revolution at that time; suddenly everyone was into conservation and heritage, the budgets went up and we started recruiting specialist staff and that continues to this day.*" (FC-G, p3)

Whatever the cause, the change in the Forestry Commission approach has been recognised by all stakeholders who stress that the change in focus is much more on recreation and wildlife than previously:

"*There's a massive newspaper that came out the other day to do with the Galloway Forest Park, just talking about the recreational uses of the forest and all these bike trails, more and more to do with fishing, and I'm sure they make losses on all these things, but its totally changed from being purely economical.*" (GFT)

The change is seen as being permanent by all sides of the debate; when asked the question "*Do you think the Forestry Commission's position would be different if timber prices doubled?*" no stakeholders could envisage the FC position changing (Table 3-4).

Table 3-4 Permanency of "Multiple Value Forestry"

"Do you think the Forestry Commission's position would be different if timber prices doubled?"	
GFT	"I don't think it can now... the people they employ have got different views"
GFT-S	"I don't know what their attitude would be... I think they would be called to order if they said 'we really are commercial – and look how much money we're making!'"
SEPA-G	"No. I don't think they would now. Under the current management, the current director for Scotland is very conscious of the environment, as is [the Forest District Manager] down here in Galloway."
FC-PP	"It would not cause us to re-evaluate these environmental and social concerns, but it would perhaps make it more difficult to resolve the balance for particular areas... on the other hand the fact that there is a certification process that means to get the logo and guarantee market share these environmental and social aspects have to be fulfilled."
FC-G	"[No,] in fact what's difficult to balance is just how much straightforward Sitka spruce production there is ... we've got vast areas of 'tree factory' in Galloway which are accessed by mountain bikers and walkers in [great] numbers"

Whilst these views suggest that changing institutional views have significantly changed the approaches of forest practice: the guidance regarding acidification within the second, third and fourth (see Chapter 4 :) editions of the Guidelines have changed very little in terms of its overall tone; they all present pragmatic science-based approaches to the identification of areas at risk as the solution to the mitigation of the "forest effect". There is little acknowledgement of the complexity of the issue, or encouragement to take a precautionary approach regarding ecological impacts: the Critical Loads model and the 300m rule are presented in the Guidelines as sufficient to identify areas at risk. Chapters 7, 8 and 9 investigate the extent to which this is the case.

3.3.4 Forestry and acidification in practice

It is clear that the *Forest and Water Guidelines* were well received as an approach to minimising the impacts of forest operations, and that the position of the Forestry Commission in relation to environmental issues has shifted significantly. However, the approach put forward by the guidelines to address the problems of acidification were not well received, especially in Galloway. The early editions of the Forest and Water Guidelines "*did not address acidification problems properly and in fact were greeted with howls of derision by the vast majority of environmentalists*" (Stephen, 1994b). A worked case-study of Galloway helps to illustrate why this was the case.

3.3.4a Restocking/ Replanting

The single key problem with the 2nd and 3rd editions of the *Forest and Water Guidelines* was that the guidance applied only to new plantings, and not to "restocking": the replanting of areas that had already been planted. This was a significant issue in the eyes of Galloway fisheries stakeholders for both its logical inconsistency and its practical implications.

"*the sticking point locally had been – if you have an acid-sensitive geology which, under the terms of the guidelines you cannot plant were it to be a first planting – where is the justification for replanting and reintroducing the problem that you wouldn't actually put there in the first place were it pristine ground?*" (GFT-X*)

"*the early [editions of the Forest and Water Guidelines] didn't really recognise the problem – the direct link – until the [fourth edition] they didn't address replanting – there's still this assumption that you must replant these areas, and the full acceptance amongst everyone that if there were no trees there now you would never be allowed to plant them because they would fail everything – but because they were there already you actually have to replant them – its stipulated in the grants system*" (GFT)

3.3.4a(i) Forestry Commission justification: A pragmatic approach

The Forestry Commission explains that the decision to exclude restocking was made for pragmatic rather than scientific reasons. They emphasise that is important that the *Forest and Water Guidelines* are practically applicable and that if the approach considered restock across the "*whole forest estate*" including "*every catchment*" it would be "*a huge task*". Instead the intention has been "*to target those sites which cause the greatest risk*". They stress that "*they don't see restocking as posing as much of a risk as a new planting*" as for new plantings "*you're changing the land use to one with a greater scavenging*" (FCH).

Whilst this is an understandable position from an organisational point of view, the logical inconsistency does undermine the scientific credibility of the approach to an extent. Concepts from science (scavenging, occult pollution, Critical Loads) are used to make decisions about the areas at risk but only if those areas of risk have already been deemed appropriate on the basis of management practicalities.

The Forestry Commission itself recognise the problem and updated the 2003 guidelines to include both restock and new plantings recognising that they "*could no longer defend just restricting consideration in terms of acidification to new plantings*" (FCH). The Forestry Commission spokesperson stressed, however, that the *Forest and Water Guidelines* are "*a step process*" that is updated regularly and that "*if subsequent research shows that we've not quite got it right*" they are open to change, stating "*as I say, last time we didn't even deal with restock*" (FCH). It must be remembered that it was not just the Forestry Commission making these guidelines, and that they were agreed by a multi-organisation working group including SRPB/SEPA representatives. Nevertheless, the guideline was in place for 10 years, 1993-2003.

3.3.4a(ii) Management implications

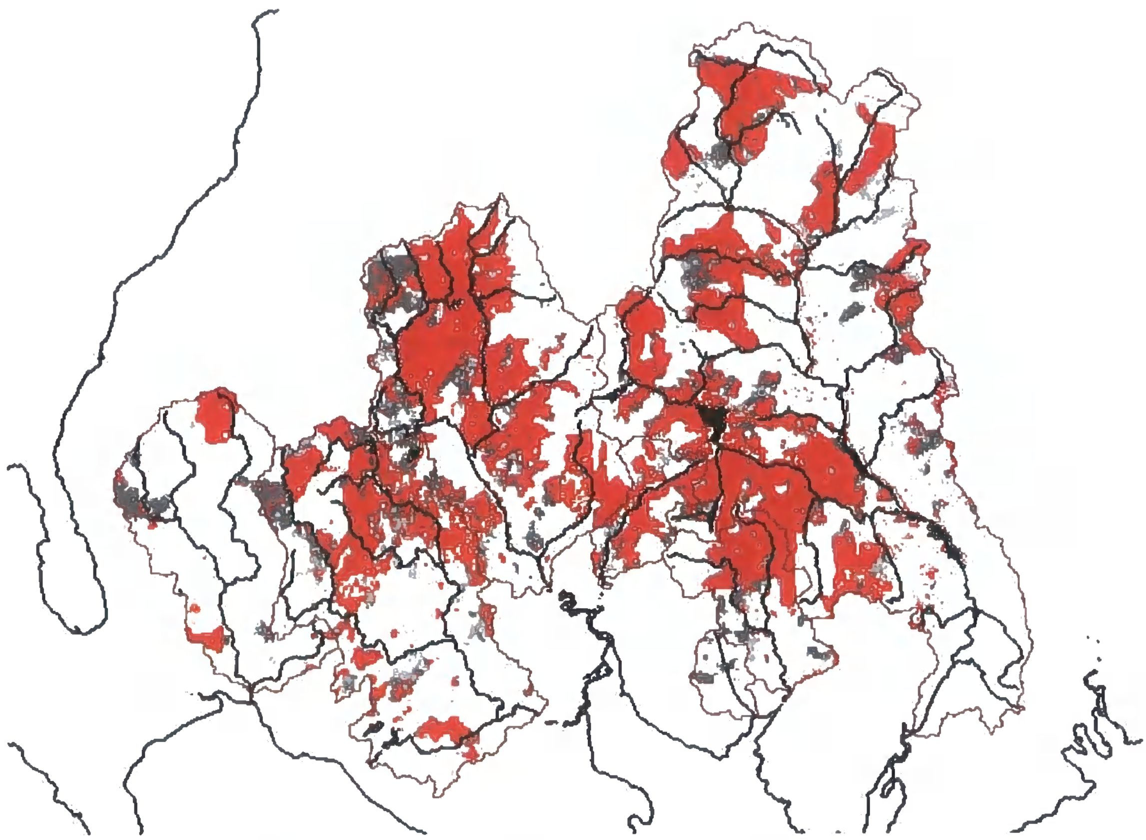
Figure 3-4 shows the proportion of the Galloway region under canopy-closed forestry at four time stages. Trees are expected to reach canopy closure at around age 15 (Nisbet, 1990; Forestry Commission, 2004), if this is assumed to be the case, then all the trees shown as canopy-closed before 1995 were planted before 1980, all those shown as canopy-closed in 2001 were planted around 1985, and all those canopy-closed in 2005 were planted around 1990. This would mean that the shown as canopy-closed in 2005 was planted prior to the introduction of any guidance in terms of acidification.

Even if a forest were to achieve canopy closure in 10 years, it is only the trees shown as canopy-closed in 2001/2005 (shades of grey in Figure 3-4) that would have had to take the guidance on acidification into consideration, and of these those canopy-closed in 2001 (dark grey) are most likely to have been planted with the agreement to lime under the second edition, an aspect that was removed in the third.

It is fair to conclude therefore that, in practice, the early versions of forest and water guidance for acidification did not contribute to the reduction of any "forest effect" in the Galloway region, for the simple reason that there was very little new planting in the region for the policy to apply to.

Figure 3-4 illustrates therefore that, by taking a pragmatic approach and excluding restocking in the early editions, the Forestry Commission not only undermined the scientific robustness of their own methodology but led to a position where the guidelines had almost no management implications for forest practice in Galloway.

Figure 3-4 Galloway Plantings 1989-2005 (canopy-closed forest cover change)



1989		1995		2001		2005		TOTAL 2005	
BL	2.2 k ha	BL	+ 2.8 k ha	BL	+ 0.3 k ha	BL	+ 2.4 k ha	BL	7.8 k ha
CR	8.1 k ha	CR	+ 1.9 k ha	CR	- 1.0 k ha	CR	+ 0.4 k ha	CR	9.4 k ha
DE	13.9 k ha	DE	+ 4.5 k ha	DE	+ 0.0 k ha	DE	+ 1.9 k ha	DE	20.2 k ha
FL	1.4 k ha	FL	+ 0.7 k ha	FL	+ 0.3 k ha	FL	+ 0.2 k ha	FL	2.6 k ha
LU	0.6 k ha	LU	+ 0.5 k ha	LU	+ 0.3 k ha	LU	+ 0.1 k ha	LU	1.5 k ha
PA	0.8 k ha	PA	+ 0.5 k ha	PA	+ 0.2 k ha	PA	+ 0.2 k ha	PA	1.7 k ha
SK	0.0 k ha	SK	+ 0.0 k ha	SK	+ 0.2 k ha	SK	- 0.2 k ha	SK	0.0 k ha
GW	**27.0 k ha**	**GW**	**+ 10.9 k ha**	**GW**	**+ 0.2 k ha**	**GW**	**+ 5.0 k ha**	**GW**	43.1 k ha

Values in 1989 are canopy-closed forest cover. Values in all other years are increases from the previous year

3.4 Summary

This chapter introduced the *Forest and Water Guidelines* the policy response by which the Forestry Commission address the potential impacts of forestry on water quality. It showed that the Guidelines are seen by the Forestry Commission as a good set of best practice guidance that places the FC at the forefront in terms of dealing with diffuse pollution and addressing the challenges raised by the WFD. An overview of the scientific understanding of the "forest effect" was presented with particular reference to the ways in which it influenced the Forestry Commission's policy response. The Forestry Commission's approach to understanding the "forest effect" was shown to draw largely on scientific evidence, with a high level of scientific proof required to influence change. They required the "forest effect" mechanism to be understood before any policy action would be taken and selectively dismissed scientific evidence from paired catchment studies and regression based approaches as insufficient proof for the development of guidance. Similar to Jordan and Greenway's (1998) example of British Water Pollution Policy 1995-1995 changes in policy response resulted from "*exogenous shocks [from] outside the system*" in the form of pressure from outside organisations the Water Research Centre (1st edition) and the Acid Waters Review Group (2nd edition) rather than initiated by the Forestry Commission itself.

The reason for the Forestry Commision's reluctance was focused around evidence for a "forest effect" *per se.* which the Forestry Commission did not view as sufficient. The Darlington meeting in 1990 was shown as a key moment in the "forest effect" debate; at this meeting the Forestry Commission and the academic community reached an agreement and discourse surrounding a "forest effect" *per se.* was replaced by a discussion of the "forest effect" of sulphate scavenging.

Whilst the Forestry Commission framed their discourse in the face of Welsh Water and the AWRG in hard-line scientific terms, the single most influential rule governing the impact of the *Forest and Water Guidelines* in Galloway was made based on pragmatic rather than scientific reasoning. As having the guidelines apply to the whole forest estate was seen to be a huge task, the guidance was restricted to new plantings; this led to the guidelines being almost ineffective in Galloway. From a social constructivist point of view this is highly significant: pragmatic concerns which are "*taken for granted*" (Latour and Woolgar, 1979) in the Forestry Commision's discourse around the *Forest and Water Guidelines* as a Science-based approach are, in practice, the controlling factor determining the extent to which both policy and practice were able to influence the "forest effect" from the introduction of the guidelines until 2003.

From 1993-2003 guidance for acidification within the third edition of the *Forest and Water Guidelines* has not significantly changed: the institutional drivers behind the Forestry Commission have been shown to have changed significantly with the introduction of Forest Enterprise recognising that the Forestry Commission's role is one beyond simply forest industry; a role that considers multiple values of forestry. Chapter 4 : (next) introduces the fourth edition of the *Forest and Water Guidelines*: this updated guidance removes the restocking/replanting rule and so provides new potential for the *Forest and Water Guidelines* to mitigate acidification in Galloway Forest District. Chapter 5 then takes a long-term view of the "forest effect" similar to that of this chapter but from the view of local Galloway stakeholders; it explores the factors that influence forestry policy and practice whilst the restocking rule prevented the *Forest and Water Guidelines* from contributing to management change.

Chapter 4 : Acidification in the 4th Edition of the Forest and Water Guidelines and Galloway

4.1 Introduction

In 2003 the Forestry Commission introduced the 4th edition of the *Forest and Water Guidelines.* The FC see these Guidelines as the approach by which forest management can identify and manage areas at risk of failing the needs of the EU Water Framework Directive (section 3.1.2a). Through extending the guidelines to cover both new plantings and re-stocking, this edition of the Guidelines has the potential to have a far greater impact on the water environment than the previous three editions, particularly in Galloway (Cf. section 3.3). This chapter draws on policy and literature review, participant observation and semi-structured interviews with the local Galloway stakeholders to focus on three main topics:

1) The representation of the "forest effect" within the 4th edition of the *Forest and Water Guidelines* and the redefined risk-based approach to forest management.

2) A discussion of the concerns of local stakeholders regarding the approach to acidification within the 4th edition Guidelines: Local stakeholder's are shown to perceive a wider "forest effect" beyond that identified by the *Forest and Water Guidelines.*

3) A critical re-investigation of the academic literature in an attempt to determine whether existing supporting evidence is present for a wider "forest effect" in Galloway.

The chapter ends with a summary of the current situation in the Galloway region in terms of the uncertainties around the extent to which the understanding of the "forest effect" represented in policy contributes and effective approach to tackling acidification.

4.2 Introducing the 4th Edition Forest and Water Guidelines

4.2.1 The 4th Edition

The fourth edition of the *Forest and Water Guidelines* (Forestry Commission, 2003b) and is the only document by which *forestry practice* within the UK is modified for the purposes of minimising the risks that acidification poses to the achievement of the WFD's aim of "good ecological status". It therefore represents the transposition of EU legislation for the purposes of forest management and provides the policy context for this thesis. As a result, the second research question set in section 1.4.1b becomes:

- What factors influence the extent to which Best Available Knowledge of the "forest effect" is incorporated in the 4th edition of the *Forest and Water Guidelines*.

To begin to address this question this chapter explores the relationship between the "forest effect" presented in the *Forest and Water Guidelines* and the varied knowledges held by local stakeholders (FC-G, SEPA-G, SEPA-WFD, GFT, and GFT-S).

4.2.1a Forestry Commission guidance for acidification in the 4th Edition.

The 4th edition of the *Forest and Water Guidelines* significantly changes the guidance for acidification from that in the previous editions. It includes minor updates in line with current scientific understandings of acidification, adding an extended discussion of the role of nitrogen deposition following the reports of NEGTAP (2001) that demonstrated the 71% decline in sulphate emissions (1970-1999) has led to nitrogen emissions exceeding sulphate. It also includes additional guidance for minimising the impacts of nitrate leakage following clear felling following Neal *et al.* (1992). Most significantly however the guidance has been extended to cover to both new plantings and restocking.

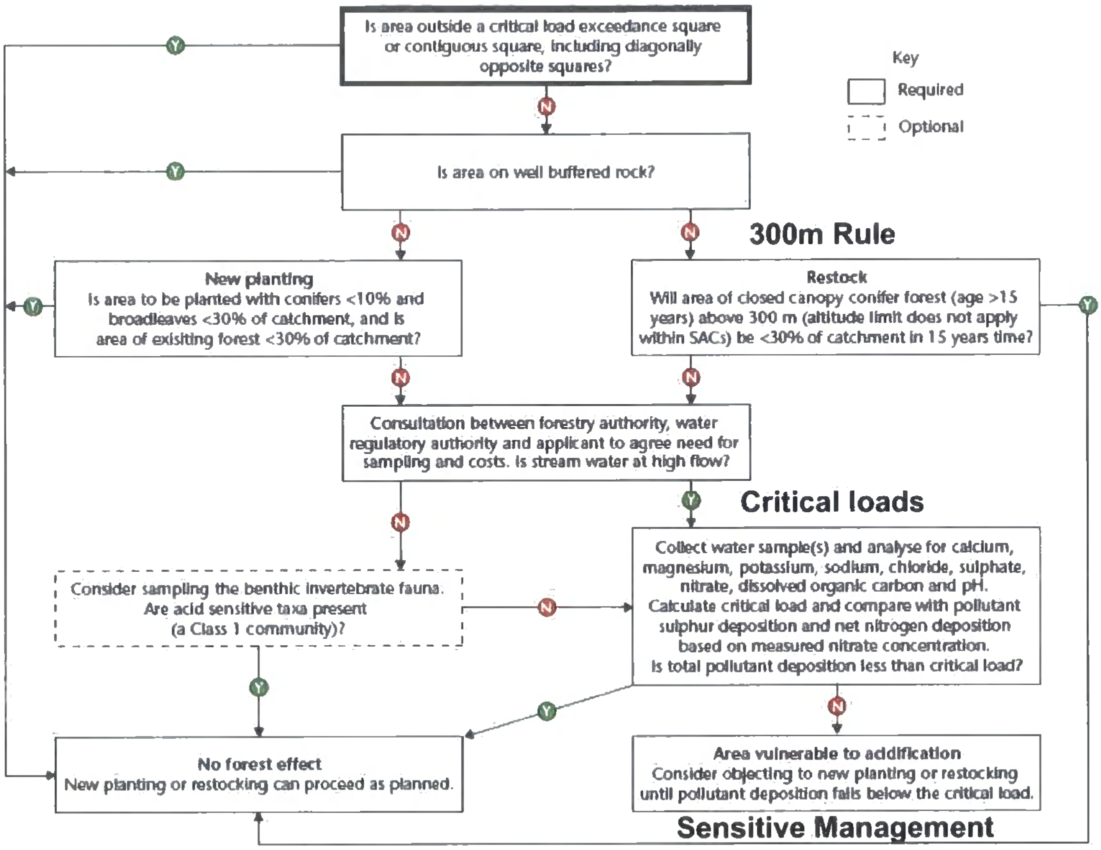
4.2.2 An Overview of 4th Edition in practice

Figure 4-1 shows the schematic of the new approach to acidification in the 4th edition of the *Forest and Water Guidelines.* The approach taken by the Forestry Commission is a "sifting process", similar in style to that in the earlier editions where the aim is to focus on the areas of greatest risk. This section follows a step by step approach through the guidelines to illustrate its potential for impacts *in practice* using Galloway Forest District as a case study.

4.2.2a UK Critical Loads Exceedance squares

The first step in the decision making process is followed irrespective of whether the site under consideration is a new planting or an application to restock; a site is checked as to whether or not it is in a square picked up as exceeding Critical Loads at a UK scale using the UK map of Critical Loads exceedance for 1995-97 produced by the Environmental Change Research Centre (Hall *et al.*, 2003; Hall *et al.*, 2004). The squares used are 10km^2 in which the critical load exceedance has been calculated for the most sensitive water body within that square. The Forestry Commission also considers all squares adjacent (including diagonally) to these squares as a precautionary measure reflecting the "indicative only" nature of the maps.

Figure 4-1 Forest and water guidelines decision tree (from FC, 2003b)



The entire Galloway region is either under a Critical Loads exceedance square, or adjacent to one, and as a result this step of the forest management process receives no criticisms from the Galloway stakeholders. It is as a result of the inclusion of adjacent squares that the Forestry Commission feels that it is necessary to perform a further sifting process:

"*because we've extended into all the adjacent squares ... we're moving to a wider area and there's going to be less sensitivity in parts of those; particularly in terms of geology because we've moved off the main Critical Loads exceedance squares. So we need to factor in geology and take out those that are clearly better buffered.*" (FCH)

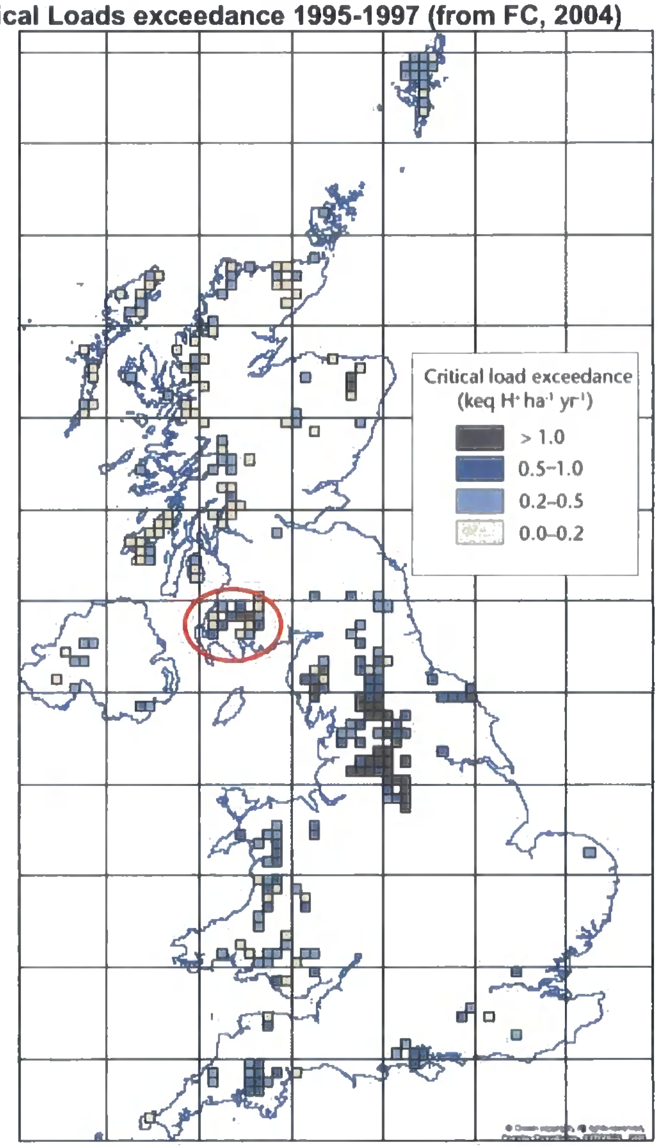
4.2.2b Well-Buffered Rocks

The second step involves determining whether a site is on "well-buffered rocks" (FC, 2004); if it is it, is considered safe from any forest effect. This step was added to reduce the area covered by the guidelines in compensation for the inclusion of the adjacent Critical Loads exceedance squares. The actual definition of "well-buffered rocks"[12] is not present in the *Forest and Water Guidelines*; however FCH (*pers comm.*) indicates

[12] In fact, it is the soils that are well buffered rather than the rocks.

that in Galloway none of the rocks present are currently considered "well buffered" and so there is little conflict between stakeholders over this decision either.

Figure 4-2 UK Critical Loads exceedance 1995-1997 (from FC, 2004)



4.2.2c New Plantings

It is at this point in the guidelines where the advice splits depending on whether the considered application is a new planting or a restocking of previously afforested land.
In the case of a new planting the guidance is more strict: if the planned planting will entail over 10% of a catchment under conifer forest or 30% under broadleaves or the intended catchment already contains greater than 30% forestry, then it is necessary to contact the water regulator (in Galloway: SEPA) in order to perform a catchment-based Critical Loads test in the same way as in the third edition.

New plantings are not as common in Galloway as restocking (as demonstrated in 3.3.4) and were not raised as an issue by stakeholders; however, concerns existing over the use of the Critical Loads model at a catchment scale (4.2.2d, next) apply as much to new plantings as they do to restocking; these are discussed in section 4.3.1.

4.2.2d Catchment-based Critical Loads exceedance

The catchment-based Critical Loads approach used is the same as that introduced in the third edition of the guidelines and outlined in section 3.2.6a. It uses a water sample collected from a high-flow event to determine the buffering capacity of the catchment. It compares this with modelled deposition from 1995-1997 CEH deposition data; this is an update on the 3rd edition which used 1986-1988 data. A more recent (2003) sulphur deposition dataset is available, but the 1995-7 data are used as a "*precautionary measure*" (FCH). An ANC value of zero is still used, and it is stressed that as this is for a high flow sample; it can be seen to be at least equivalent to a median flow ANC of 20, as ANC is known to decrease as flow increases (FCH: see section 7.2.2).

The use of the Critical Loads model at a catchment scale is a source of concern amongst stakeholders; this is discussed in detail in section 4.3.1.

4.2.2e Restocking and the "300m rule"

The guidelines for restocking are less strict, reflecting the Forestry Commission's belief that restocking brings less additional acidification than the land use change that comes with new plantings (3.3.4a(i)). If the site has already been planted then any area under 300m may automatically be replanted without needing any further considerations. However, in high altitude catchments where, as a result of restocking, over 30% of the area over 300m within a catchment will become closed canopy forest (defined as >15 years in age) in the future then the forest manager must contact the water regulating body in order to perform a catchment-based Critical Loads test. As a response to lobbying from fisheries stakeholders (GFT; see 5.3.1b(iii)) during the consultation period the FC added an exception to this rule for areas Special Areas of Conservation, in which case the test is necessary irrespective of altitude.

The "300m rule" is a contentious issue amongst Galloway stakeholders; this is discussed in detail in section 4.3.2.

4.2.2f Sensitive Management

At the end of the process, if the area is: in, or adjacent to a critical load square; on a sensitive geology; will have over 30% of the area covered in canopy-closed conifers;

and fails a Critical Loads test, then: the water managers may "*consider objecting to the planting until pollutant deposition falls below the critical load*".

Galloway stakeholders do not object to the approach to sensitive management; in fact the fisheries stakeholders recognise it as "*heavy control*". The concern instead lies with the ability of the Critical Loads model and the 300m rule to identify the areas in which these controls should be applied.

4.3 Stakeholder Views of Forest and Water Guidelines v4

The Forestry Commission defends the choices it has made in the *Forest and Water Guidelines* as a) scientifically based and b) a jointly badged document agreed by an inter-agency group including environmental regulators (section 3.1.2b). When considering the Galloway stakeholders it is clear that whilst they recognise themselves as "signed-up" to the *Forest and Water Guidelines*, and support what they stand for, they have at best, a lack of knowledge about the specifics of the approach and at worst, significant distrust of their suitability for the task of determining areas at risk.

This section explores the factors that lead to discord between local knowledges and the view of risk presented by the *Forest and Water Guidelines* focusing on the two main sources of contention: a) the use of the catchment-based Critical Loads methodology; and b) the 300m rule.

4.3.1 The Critical Loads approach: an accepted methodology

4.3.1a "Expert" knowledge

The Critical Loads model is a key source of disagreement between local stakeholders and the *Forest and Water Guidelines*: local stakeholders recognise the approach as an "*acknowledged methodology*" (SEPA-WFD*) and recognise fact that they have "*signed up to it*" (GFT). It is, however, very much seen as an "expert" approach and both the local Forestry Commission and the Galloway Fisheries Trust (GFT) are taking it on faith that the method will meet their needs.

"*I don't talk with confidence about the critical load system; I've heard it's a very good system, there's lots of people worked on it – they've agreed it and they're experts.*" (FC-G)

"*Everything seems to stem on [the Forestry Commission Hydrologist] knowing what he is talking about, and I'm sure that he does, but it's a big gamble for everyone, you* *know; we've all signed up to it and said that it's great without anything going through it.*" (GFT)

Knowledge regarding the approach is centralised within the Forestry Commission at the policy-maker level that advocated the use of the approach. This is not a position the stakeholders are unaware of; the second quotation above indicated that the Fisheries Trust recognise that the "experts" behind the decision making come from within the Forestry Commission – notably the Forestry Commission Hydrologist. The local Galloway Forestry District Manager confirms this indicating that the Guidelines were handled at "*a very high level*" within the organisation and that as a result "*lots of practitioners felt that they'd been excluded from the consultation*".

This in turn raises the question of the extent to which the *Forest and Water Guidelines* are truly a "*jointly badged document*". This is discussed in more detail in section 5.3.2a, but with regards to the Critical Loads model it is clear that the SEPA member of the *Forest and Water Guidelines* panel's views in opposition to the Critical Loads model are relatively strong. In answer to the question "What is your view of the Critical Loads model as a way to achieve the aims of the Water Framework Directive?" SEPA-G's was: "*No. I don't think [the Critical Loads model] satisfies ...*" but that he lacks the scientific expertise to prove it: "*but I'm not a good enough statistician or a chemist to demolish it scientifically*" (SEPA-G). SEPA-G indicates that his doubts are based on his personal experience with the model and it not matching his understandings of the water environment: "*The stuff we ran on Critical Loads didn't obey any rules ... we did one project on snow melt, in spring, which should be the worst and it was the best water quality we got. I don't know how to answer that ...*" (SEPA-G).

In conclusion, stakeholder parties at a local level recognise the *Forest and Water Guidelines* as an approach to which they have signed up, and support in principle. This agreement is, particularly, in terms of the Critical Loads model, not accompanied by an understanding of the significance of this acceptance, and continues in spite of reservations of by one of the members of the guidelines panel. As a result the *Forest and Water Guidelines* reflects far more the Forestry Commission's construction of the "forest effect" than that conceptualised by the local stakeholders. The "expert" nature of the Critical Loads approach is therefore a factor that prevents non-specialist stakeholders, even those with influence over policy and reservations about the approach, from feeling confident enough to dispute the approach. Furthermore, in accepting the Critical Loads model "on faith" local stakeholders limit discussion of alternative measures. The perception of the Critical Loads model as an "expert" technique is therefore a factor that restricts knowledge transfer between local stakeholders and policy makers.

4.3.1b The approach is "untested"

The extent to which the use of the Critical Loads model is a factor influencing the ability of policy and practice to address the "forest effect" will depend on the appropriateness of the model as a method for the identification of areas in which the "forest effect" poses a risk. This was a factor that local stakeholders viewed as having been largely *untested,* certainly at a regional scale within Galloway. As a result, local stakeholders were unable to pre-judge the effectiveness of the approach in practice: and thus identify its significance in terms of potential management implications. This was a concern raised by both the Forestry Commission at a district level and the Galloway Fisheries Trust.

From the Forestry Commission District viewpoint, concerns were raised over potential impacts was in terms of economic costs: "*we had no idea when we entered into this what the outcome would be … it could have been absolutely terrible or it could have been insignificant; it could have been costly or it could have been cheap; we just didn't know*" as a failure of the critical "*in more than 1 or 2 samples*" could potentially lead to "*thousands of hectares destroyed and left deforested for a considerable length of time*" an impact that would be "*very very difficult to manage*" (FC-G). They add that much of the confusion for forest practitioners could have been reduced if the Forestry Commission had done "more consultations in the industry and in trials to demonstrate the potential impacts economically and environmentally" (FC-G).

The Galloway Fisheries Trust has a similar view of the untested nature of the approach, but with the inverse concerns: "*the trouble is that everyone has gambled on this critical load really making a difference but none of us are detailed chemists, [there've been] no trials in acidified areas … if everywhere passes then there's no point [to] all these heavy controls that we've brought in*" (GFT)

They key concern for local stakeholders is therefore uncertainty over the scale of the impact the Critical Loads model will have across the region. As specialist knowledge regarding the Critical Loads process is centralised within the Forestry Commission at policy making and research science levels, local stakeholders do not have enough information on where the Critical Loads model will pass or fail to fit that to a) their understandings of ecological impact and b) the level of economic impact to the Forestry Commission.

It is interesting to note the impact of the restocking/replanting rule (section 3.3.4). Critical Loads at a catchment scale is *not*, of itself, new to the guidelines; it was introduced in the third edition (1993); the fact that it is treated as new by both Fisheries Trust and the GFDM reinforces how little effect the new planting guidance in the previous editions had (section 3.3).

4.3.1c "The approach is not appropriate"

In addition to the arguments over the untested nature of the approach, there exist arguments that the method was not appropriate, that a) modelling has too many uncertainties, b) the choices made within the model were wrong c) the model does not match local knowledge.

4.3.1c(i) Too many uncertainties

Those stakeholders with greater understandings of the Critical Loads approach, raise concerns over the use of a modelling approach in general, especially in terms of the choices made within the models. The SEPA representative on the *Forest and Water Guidelines* (SEPA-G) explained that drawing on his experience of "*the results of sampling over the last 15 years*" he believed that "*the environment is far too complicated*" to model and that "*in terms of determining the sensitivity of water courses" he was "not a great fan*" of the Critical Loads approach. He argued that there were too many "*fiddle factors*" within the methodology for it to be used for catchment-scale decision making.

This view is reinforced by the views of Tervet *et al.* (1995) who investigate the impacts of the use of constants from national-scale databases rather than field measured values for rainfall and sulphate deposition within a worked example of 80 streams from the Galloway area. The paper was co-authored by representatives of the Solway River Purification Board and the Galloway Fisheries Trust, and followed the Forestry Commission chosen Critical Loads methodology (CLAG Freshwaters, 1995). and demonstrated that a) the use of standard constants within the model rather than local detail can lead to differences of critical load in the order of 0.3 μeql^{-1} for extended periods b) for a significant number of streams with pH<5 Critical Loads were not exceeded c) that even when Critical Loads were not exceeded by as much 1 keq $ha^{-1}year^{-1}$ there was no certainty of trout presence and a potential for of salmon absence and d) modelled sulphate deposition could be as little as half that of field measured deposition. These uncertainties led them to declare "*the use of the steady state model as a catchment management tool requires considerable caution*" and suggest that *"streams should be considered as potentially at risk unless the critical load exceeds deposition by at least 1 keqha-1year-1"* (Tervet *et al.*, 1995).

General concern over the applicability of the model for catchment decision making is reinforced by Barkman (1998) who stresses that *"the inevitable presence of uncertainties in the Critical Loads approach makes the concept more appropriate as an instrument in environmental risk assessment rather than defining an exact response to a pollutant"*.

4.3.1c(ii) The choices in the model are wrong

The choice of ANC limit was also an issue raised by the Scottish Environmental Protection Agency representative on the *Forest and Water Guidelines*. SEPA-G argued that the ANC_{LIMIT} value of zero standard set in the UK was not as tight as that set by the Scandinavians: *"They have a much better relationship in terms of anions and cations when they're setting up the acid neutralising capacity of river systems. We allow zero – i.e. totally matched up- whereas they like 50; they want 50 cations in advance of anion balances; a much safer figure to be working to."* (SEPA-G). this view is also supported in the academic literature, with Bridcut *et al.*(2004) arguing that to incorporate acid pulse episodes an ANC_{LIMIT} value of 39 μeql^{-1} should be set for a 50% probability of brown trout occurrence. The Forestry Commission argue that using a high flow ANC_{LIMIT} = 0 is justified as it is more than equivalent to a base flow ANC_{LIMIT} of 20 (see 7.2.2a(ii)) used for the UK national Critical Loads exceedance maps developed by CEH (Hall *et al.*, 2003; Hall *et al.*, 2004).

4.3.1c(iii) The model does not match ecology

Fisheries stakeholders and local Forestry Commission staff do not make their arguments in terms of the inner workings of the Critical Loads model. Instead they are interested in whether the method matches with their own understanding of the ecological condition of the rivers. Those stakeholders that have seen any results of Critical Loads sampling raise questions over the fact that the critical load model is capable of passing in areas that are too acidified for fish.

Fisheries stakeholders question whether it is an appropriate technique to identify the areas at risk *"the actual critical load process has been in doubt - to put it mildly – I mean it seems to pass in areas cannot survive when planted – so are they doing the job they should be doing? Particularly in an SAC where the salmon is the key point of the SAC?"* (GFT-S).

Similar concerns were also expressed by the Forestry Commission at the district level after the preliminary results of the 2005 survey: "*The thing that worries me about [the Critical Loads model] is the linkage with biological data. For example with the Bladnoch we had only one slight failure of Critical Loads – very marginally. But ... the second to worse one, that's got salmon in it! I couldn't figure out how in a district where we have many many fishless streams we have got salmon in those streams*" (FC-G).

4.3.1c(iv) The Critical Loads model: an appropriate approach?

Whilst these concerns raised above are all valid, their significance in terms of the appropriateness of the approach is difficult to determine due to the "untested" nature of the approach at the scale of the Galloway region. Without a regional scale understanding of the areas identified as at risk by the model it is impossible for stakeholders to truly judge the impact of the methodology in practice. As a result generating maps of regional Critical Loads sensitivity and exceedance was identified as priority for quantitative research within this thesis (see Chapter 5): the field survey methodology is discussed in section 6.2.1c and the maps are presented in section 7.2.2.

4.3.1d Fitting in with National Science

Although not raised as an issue by any of the Galloway Stakeholders it is important to note the ways in which the approach taken by the Forestry Commission varies from that taken by the official UK Critical Loads scientists. Since the original CLAG (1995) followed by the Forest and Water Guidelines the Critical Loads methodology has been updated significantly to include both a modified ANC of 20 rather than zero (Hall *et al.*, 2003; Hall *et al.* 2004) and to prefer the First-order Acidity Balance Model (FAB; Curtis, 1998) to the Steady State Water Chemistry Model of Nilsson and Grennfeldt (1988), as the FAB model is better designed to take catchment Nitrogen processed into consideration (Curtis *et al.*, 1998). The Forestry Commission are aware of these updates but believe that a) the ANC of zero is justified as they use high flow samples (7.2.2a(ii)) and b) that the flexibility offered by the SSWC model's dependence on a single field sample is sufficient justification to use it over the more extensive data requirements of the FAB model (FCH, pers. comm). The extent to which this decision of model is a factor influencing access to Best Available Knowledge will depend on the extent to which the SSWC model is fit for the task it is being put; this is discussed further in Section 7.2.2.

4.3.1e Alternatives to Critical Loads

It is easy to criticise the Critical Loads model; however, no stakeholders dispute the need to separate those catchments at risk from those that are not for the purposes of management. As one SEPA stakeholder points out, it is an "*acknowledged methodology*" for determining the impacts of pollutant deposition on water bodies, with a history of use as a decision making tool. He argues that "*[you can] have a straight debate about whether it is robust or not to identify what is required but ... in the absence of an alternative I think that its easy to say that the method does not work, its less easy to come up with one which is accepted*" (SEPA-WFD).

Some stakeholders argue that they would prefer something more simple, based on directly measured, rather than modelled, parameters. The SEPA *Forest and Water Guidelines* panel member suggests that "*I think you'd get a simpler fish and chemistry based system using pH and aluminium.*" (SEPA-G). The local Forestry Commission Manager agrees regarding aluminium: "*I was having this conversation with the [Forestry Commission Hydrologist]; I would like easier parameters to measure. Critical Loads analysis – you've got to measure loads of different things, and then it's not clear what's killing the fish. I'm totally happy being convinced that Critical Loads is the best integrated model, but I would like to know what is killing the fish; and it's the aluminium.*"

In making this argument both stakeholders miss the key reason for the Forestry Commission policy makers use of the Critical Loads model. The Critical Loads model is used as it is an approach that reflects the Forestry Commission's conceptualisation of the "forest effect" based on the mechanism accepted at the Darlington meeting (section 3.2.5): the "forest effect" results from *increased capture of airborne pollutants*. The Critical Loads model is used as it takes both pollutant deposition and water chemistry into consideration. The *Forest and Water Guidelines* argument is that if there is no enhanced deposition of pollution, there is no "forest effect" and the pH and aluminium in the rivers would be there irrespective of the trees – it would be a return to non-forest exacerbated acidity (see also 7.2.4).

Using a measured parameter that is an indication of *acid impact*, such as pH or aluminium, and thereby excluding enhanced deposition from the decision making process, presupposes a wider "forest effect" beyond those presented in the guidelines. The focus of local stakeholders on measuring variables that indicate *acid impact* suggests that they view the "forest effect" differently to the *Forest and Water Guidelines*: Local stakeholders focus on knowledge of impacted areas and, following an inductive approach, identify a "forest effect"; conversely, the *Forest and Water Guidelines* follow a deductive approach to identify areas where the scavenging mechanism suggests an impact is likely. These two contrasting views are even more apparent in the discussion of the 300m rule that follows.

4.3.2 The 300m rule for restocking

The restocking/replanting problem from the first three editions of the *Forest and Water Guidelines* (section 3.3.4) was removed in the fourth edition of the Guidelines. Nonetheless, as noted in section 4.2.1a, the rules remain different for re-plantings than they are for newly planted areas. Whereas a newly planted area requires a Critical Loads test whenever a catchment is to be planted with over 10% conifer or 30% broadleaves irrespective of altitude, a re-planting need only consider a test if the planned forestry will result in a canopy-closed forested area of over 30% above 300m.

This not only means that a greater proportion of conifer forestry can be planted before a Critical Loads test is required (30%), but also that restocking can continue without any need for a Critical Loads test if the planting will not lead to over 30% of the area above 300m being planted.

This is an area of significant concern for the Fisheries Trust:

"*We have a concern, particularly with this 300m rule; it's like the River Fleet which is nearly the most acidified river in the region, none of it is above 300m … the river Bladnoch is only included because its an SAC, none of it is really above 300m – they are heavily, heavily impacted; probably about a third of the whole Fleet is too acidified for salmon and unless they can pick these things out … the controls mean nothing*" (GFT)

This concern is supported by the SEPA member of the *Forest and Water Guidelines* panel who argues in response to the question "*The SAC and the 300m rule, are those the right areas to be focussing on?*" that "*No; I think that we're very clear now from where the problems from forestry stem in sensitive catchments, in poorly buffered catchments, but I think that as long as you have forestry you're always going to get a concentrating effect of atmospheric acidity*" (SEPA-G). This again raises the issue of the extent to which SEPA managed to successfully influence change within the *Forest and Water Guidelines* (see 5.3.2c).

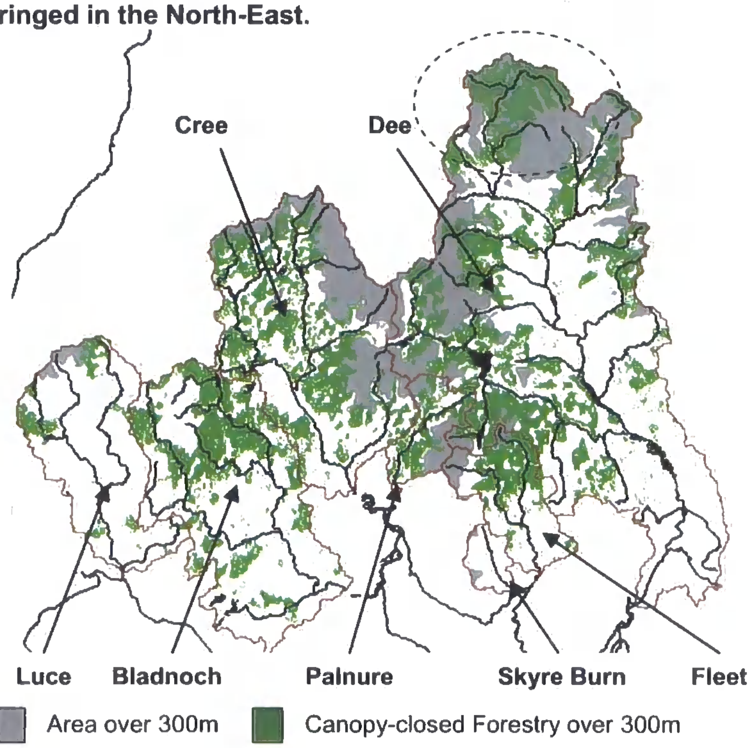
Figure 4-3 illustrates the SEPA/GFT concerns regarding the 300m rule. It shows that only 23% of the regions canopy-closed trees are over 300m in altitude, and that the Carsphairn forest in the upper Dee (ringed in Figure 4-3) is the only forest where significant proportions of its forestry over 300m.

When questioned regarding the 300m rule and the fisheries problems in the Bladnoch the Forestry Commission policy makers refer to the science-base that underpins the *Forest and Water Guidelines*. They stress that the scavenging mechanism suggests that a "forest effect" on acidification is not likely in areas below 300m:

"*Well, we have to go back to the science, and we remind ourselves that what we're dealing with here is the role that forestry has to play above what's coming into the site... we've got acid-sensitive soils and rocks and you've got naturally acidic waters, and because you've got a history of air pollution these have been acidified, and we have to then consider: putting woodland on those sites – how much worse is it going to make it? ... for the likes of the Bladnoch, where you're down at 100-150m the science would suggest that at that altitude ... scavenging is not a big issue in particular on top of the way that emissions are going and therefore it maybe below 300m we don't think that the enhancement by forestry is a significant issue.*" (FCH)

Figure 4-3 Forestry and the 300m rule in Galloway. Casphairn forest, the largest area of forest over 300m in the region is ringed in the North-East.

Catchment	Area >300m	% Forestry > 300m
Bladnoch	0.0 k ha	0 %
Cree	1.6 k ha	17 %
Dee	7.9 k ha	39 %
Fleet	0.1 k ha	5 %
Luce	0.2 k ha	11 %
Palnure	0.2 k ha	15 %
Skyre Burn	0.0 k ha	0 %
Galloway	10.1 k ha	23 %



It is, again, clear that there is a significance difference in the way that the Forestry Commission policy makers and local stakeholders view the "forest effect": for the *Forest and Water Guidelines* it is a matter of following the *agreed* "forest effect"; impacts outside of areas suggested by the scavenging mechanism are not a "forest effect"; local stakeholders however disagree, they see a wider "forest effect" based on evidence of impacts on the freshwater quality. These two different conceptions of the "forest effect" are discussed below.

4.3.3 Different "Forest effects"

The differences in opinion over both the 300m rule and the Critical Loads model suggest there are two different approaches to understanding the "forest effect": they are explained below as *mechanism-down* and *impact-up* forest effects. These effects can be seen to be analogous to the discourse coalitions of network theorists (Hajer, 1995; Bulkeley, 2000; section 2.2.1e) as they are shared storylines around common conceptions of the areal extent of the "forest effect".

4.3.3a The mechanism-down "forest effect"

The *mechanism-down* "forest effect" is the "forest effect" agreed and enshrined within the *Forest and Water Guidelines* by the process discussed in Chapter 3 :, and expressed in the second quotation above in section 4.3.2. This view states that the only "forest effect" that forest management should consider is the scavenging of airborne pollutants. This effect is greatest when there is significant cloud cover. There is therefore no "forest effect" unless there is significant cloud cover. The adoption of 300m as a cloud limit is based on work from airports (FCH, *pers comm.*) but it is 100m below the 400m limit suggested by Fowler *et al.* (1989) as the altitude where the "forest effect" was most likely to begin. For there to be a "forest effect" in the Bladnoch or the Fleet there would have to be an unexpectedly large amount low level of cloud within the catchment for prolonged periods. As this is deemed unlikely, these areas are not highlighted as at risk and any acidity present in these sites is deemed to be acidity enhanced by deposition, but not exacerbated by forestry. This approach is described as a mechanism-down approach as its fundamental approach is to determine the mechanism for the "forest effect" and allow this to determine in what areas it is possible to be at risk.

Only the Forestry Commission at a policy level (FCH, FC-PP) appear to strongly subscribe to this view of the "forest effect". All local stakeholders, whilst often describing problems in terms of a forest scavenging effect, in practice adhere to the much less well defined *impact-up* conceptualisation of the "forest effect".

4.3.3b The "wider forest effect"

The *impact-up* "forest effect" takes an inductive approach to determine what areas are recognised as affected. This approach does not differentiate between acidification in afforested areas and forest exacerbated acidification in the way that the *mechanism-down* conceptualisation does. It sees the impacts of acidity as worse within forested areas and demands management change as a result: without any need for a mechanistic explanation. This "forest effect" is inherent in any argument that forest management needs to change, or in the case of the local Forestry Commission, any change in management practices is required, in the Luce, Fleet, Cree or Bladnoch, as all these catchments have very low proportions of high altitude forestry.

The stakeholders making this argument are often not aware that they are arguing against the currently accepted "forest effect" and that for them to be right either a) the scavenging mechanism takes place at much lower altitudes than expected, and is represented by the 300m rule or b) a "forest effect" or "effects" beyond those accepted by the Forestry Commission are taking place. As such, this thesis refers to a *wider "forest effect"* it is referring to the "forest effect" as conceptualised by the impact-up view.

By arguing against the 300m rule the Fisheries Trust are shown to be of this viewpoint. Furthermore, by suggesting that variables that do not consider deposition and buffering are suitable alternatives to the Critical Loads model for identifying the "forest effect" both the local Forestry Commission and SEPA manager show themselves to follow an impact rather than a mechanism-based conceptualisation the "forest effect". As a result it appears that all local Galloway stakeholders unconsciously subscribe to a wider view of the "forest effect". It should be noted that by including Special Areas of Conservation within the *Forest and Water Guidelines* the Forestry Commission policy makers are themselves accepting the possibility of the second "forest effect" although the second quotation in section 4.3.2 suggests that they do not expect the approach to help mitigate acidification.

4.4 Evidence for the impact-up "forest effect"

4.4.1 The wider "forest effect" in the academic literature

In section 3.2.3 the academic literature up to 1991 was reviewed, as it was an agreement based on this literature that led to the scavenging "forest effect" being accepted into forestry policy and with it the "300m rule". Since 1991 however the conceptualisation of the "forest effect" within the *Forest and Water Guidelines* has not changed significantly. This section reviews the academic literature both before and after 1991 with the aim of determining to what extent evidence for a "forest effect" beyond that accepted in policy can be identified. A particular focus is paid to studies performed in the Galloway Region itself.

4.4.1a Diatom Studies

The papers that form the backbone of the Forestry Commission argument are those based on long-term diatom data, many of which were performed in Galloway. It was four lakes within Galloway's Dee system that Battarbee (1984) used to demonstrate that acidification began before afforestation. Further diatom work at Loch Grannoch (also in the Dee) provided evidence that a "forest effect" on acidification in addition to deposition-driven acidification could also be identified in the long-term record (Flower *et al.*, 1987). Kreiser *et al.* (1990) extended this work to show that Loch Chon, an afforested, high deposition site, outside of the Galloway region, showed a similar scavenging "forest effect" to that at Loch Grannoch whilst Loch Doilet an afforested site in a low deposition area showed a lesser "forest effect". They concluded: "*any acidification caused by forest growth has been minimal in comparison with the combined effects of forestry and acidification*" (Kreiser *et al.*, 1990). It is notable that the Loch Chon itself is not a high-altitude site (c. 100m) although its catchment may well extend well beyond the 300m contour.

4.4.1b Paired Catchment approaches

The paired catchment work of Harriman and Morrison (1982) and Stoner and Gee (Stoner *et al.*, 1984) were both at altitudes above 300m and so can offer no information regarding a wider "forest effect". SRPB reports from the early 1980s show that the SRPB performed *ad hoc* mini-experiments with paired catchments to inform their viewpoint and identified a "forest effect" in some: "*the pH of the heavily planted Cairnforne Burn was as low as 4.1 ... by way of comparison the nearby partially planted Pilnyark Burn was 5.5*" (Solway River Purification Board, 1983). Paired catchment approaches are not well regarded by those holding the mechanism-down viewpoint as the fundamental comparability of catchments is disputed (Nisbet, 1990b).

Tervet *et al.*(1995) drew on long-term SRPB water chemistry to compare pH, forestry and emissions for the river Cree and argued that timing of mean pH decline in the Cree matches better with patterns in afforestation than those in emissions. Furthermore, they argued that the adjacent moorland Luce retained a stable pH whilst the Cree's declined. Whilst the mechanism-based approach would argue that the use of comparative catchments is fundamentally questionable, the decline in pH was shown to be happening in spite of declining emissions, suggesting that a deposition driver may not be likely within the Cree.

4.4.1c Regional Studies

Harriman *et al.* (1987) focused on the Fleet and Dee and demonstrated that stream acidity and sulphate concentrations were significantly higher in catchments with conifer forests. The river Fleet has very little catchment area over 300m and as such evidence of a "forest effect" suggests potential for a wider effect beyond that currently considered by the Forestry Commission; however, as the relationships described in Harriman *et al.* (1987) do not separate the data from the Fleet with those in the Dee, which may well have forestry over 300m, it is difficult to draw any strong conclusions.

Wright and Henriksen (1979) indicated that there was no evidence of a "forest effect" when they had studied the western Dee, upper Fleet and Cree. Puhr (1997) however argues, drawing on Forestry Commission planting data, which the trees in these areas are unlikely to have grown to a height sufficient for scavenging at the time when Wright and Henriksen's fieldwork took place.

In 1995 Rees and Ribbens, working alongside the GFT showed that for 45 sites in the Bladnoch catchment statistically significant ($P<0.001$) differences exist between pH in catchments with canopy-closed forest cover and those with open cover. They also demonstrated by ANOVA that pH was 0.7 units lower under 80%-100% forest cover than under 0-20%. In addition, they revealed that compared to the sites with 0-80% forest cover sites with 75 trout per 100m^2 sites with 80-100% forestry had 7 trout per 100m^2. In addition they linked pH to fish data by illustrating a significant correlation (R^2 $=0.55$, $p<0.001$) between pH and trout numbers (Rees and Ribbens, 1995). This work is particularly significant as the Bladnoch catchment is below 300m (see Figure 4-3), and therefore suggests a wider forest impact beyond the currently accepted "forest effect". It is another key example of an impact-up approach to the "forest effect", and suggests no mechanism by which the forest impact is occurring, instead referencing the number of mechanisms put forward by Miller (1988) discussed in section 3.2.5d.

Puhr *et al.* (2000) drawing on a regional survey of 95 sites across the Luce, Bladnoch, Cree, Fleet and Dee found statistically significant ($P<0.01$) relationships between catchment forest cover and pH, aluminium, sulphate, chloride and sodium. This indicates a "forest effect", but as the catchments were not separated by altitude, it is impossible to determine to what extent the effect identified can be explained by the current understanding of the "forest effect". However of the catchments studied, very few have high proportions of forestry over 300m, with only the Upper Dee having a large proportion (Figure 4-3). It may well be possible therefore that the data of Puhr *et al.* (2000) provides evidence was identified for a wider "forest effect". Puhr (1997) also drew on data from 91 sites electrofished in association with the GFT to demonstrate that the percentage of sites with no salmonids increased with increasing proportions of canopy-closed forestry.

The finding of regional relationships between forestry and water chemistry reinforces the findings of Welsh Water (1987), Ormerod et al. (1989) and Gee and Stoner (1988) who using similar studies on Welsh data identified similar affects on pH, sulphate, aluminium, chloride and sodium, although not, as Rees and Ribbens (1995) did, on fish. These regression based methodologies were dismissed by the Forestry Commission as having too much scatter to be used to frame guidelines (Nisbet, 1990a; see section 3.2.4a). Puhr et al. (2000) however argue that the relationships identified can be inverted as a management tool and the scatter used as a measure of error of how accurately predictions are made stating "*it would then be up to managers to decide how to interpret the predictions and what actions to take based on the predictions*" (Puhr *et al.*, 2000).

4.4.1d Long-term studies

4.4.1d(i) The Loch Dee Project

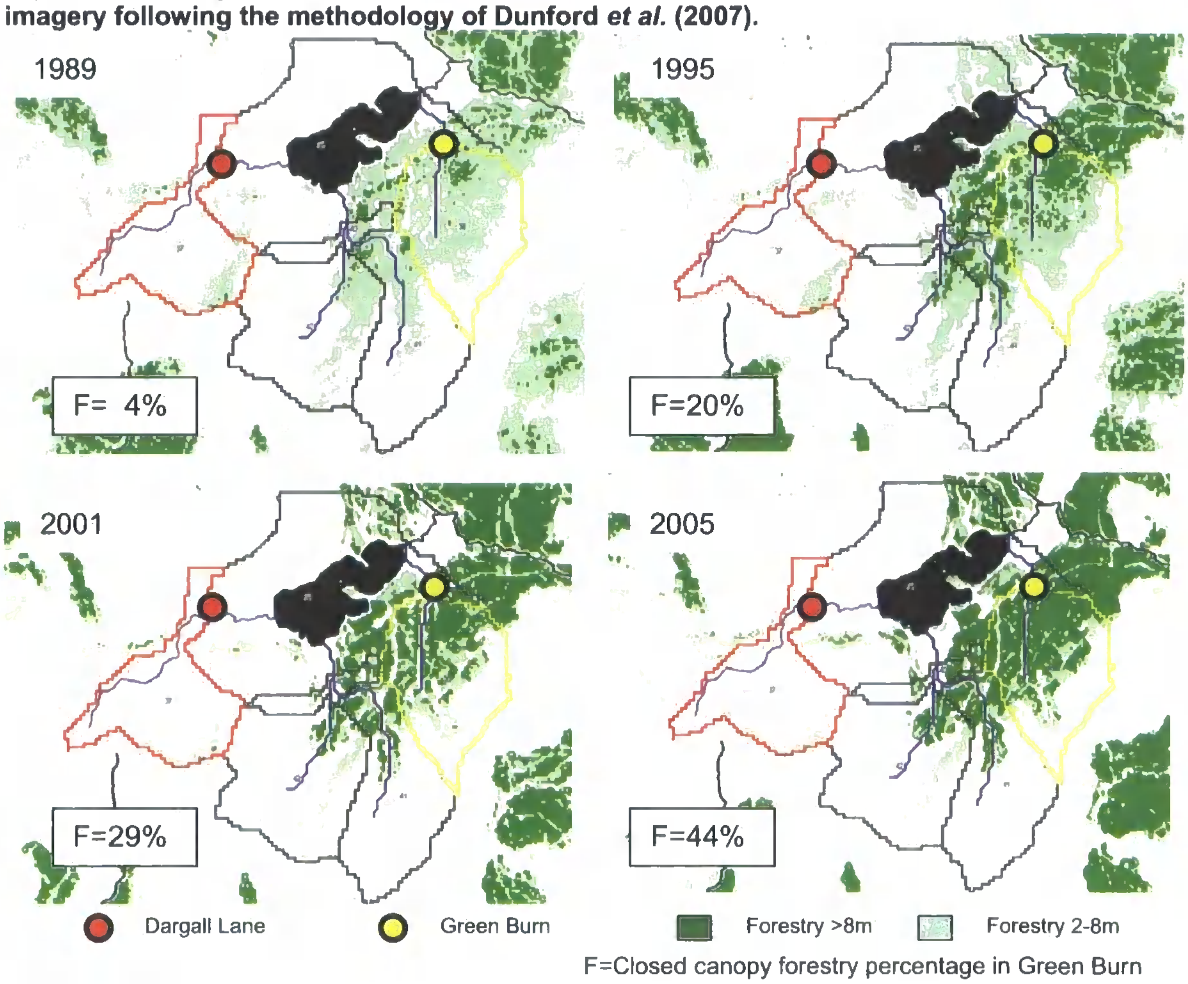
The Loch Dee Project (mentioned in 3.2.3c) is a Galloway-based experiment designed to monitor at a high resolution (weekly) the changes in water quality of a number of catchments draining into Loch Dee which was seen to have lost its fish stocks as a result of acidification. Its aim was to see if it was possible to identify a "forest effect" by comparing the moorland "Dargall Lane" with the afforested "Green Burn".

Results from the Loch Dee project were inconclusive in terms of providing evidence for a "forest effect". Flower *et al.* (1987) suggested, drawing on diatom records that forestry had little to do with the acidification at Loch Dee. In 1992 Morrison and Collen (1992) showed that fish stocks were in fact healthier in the afforested Green Burn than in the moorland Dargall Lane, a fact reinforced by Nisbet *et al.* (1993, 1995) who showed "*no evidence*" that the long-term increase in pH was "*attenuated by afforestation*".

In 1993 F.M. Lees of the Solway River Purification Board and Nisbet *et al.* of the Forestry Commission and Institute of Terrestrial Ecology, both published results in the same "Acid Reign" issue of Water Air and Soil Pollution. They both used the same Loch Dee project data but came to very different conclusions: Lees (1995) showed that a relative increase in flow weighted pH at the Green Burn site and argued that "*in the Green Burn the effect of forest growth is being balanced by sulphate emissions*"; Nisbet *et al.* (1995) showed an absence of a "*detectable forest effect*", and state that "*the magnitude of the forest scavenging effect is highly catchment specific.*".

Puhr (1997) argues that part of the reason that some authors failed to identify a "forest effect" is that, at the time of study, very little of the afforested catchment was under canopy-closed forestry, a fact recognised by both Lees (1993) and Nisbet *et al.* (1995). Figure 3-4 shows satellite derived maps of canopy closure for Loch Dee (these were developed within this project see Section Figure 3-4; Appendix B) and confirming that in 1995 only 20% of the catchment was under canopy-closed forestry. It is worth noting that this is below the limit recognised by the current *Forest and Water Guidelines* as having the potential to impact water courses, thus making the paired catchment comparisons difficult to interpret at this time.

Figure 4-4 Changes in forest cover at Loch Dee. Forest heights predicted from satellite imagery following the methodology of Dunford *et al.* (2007).



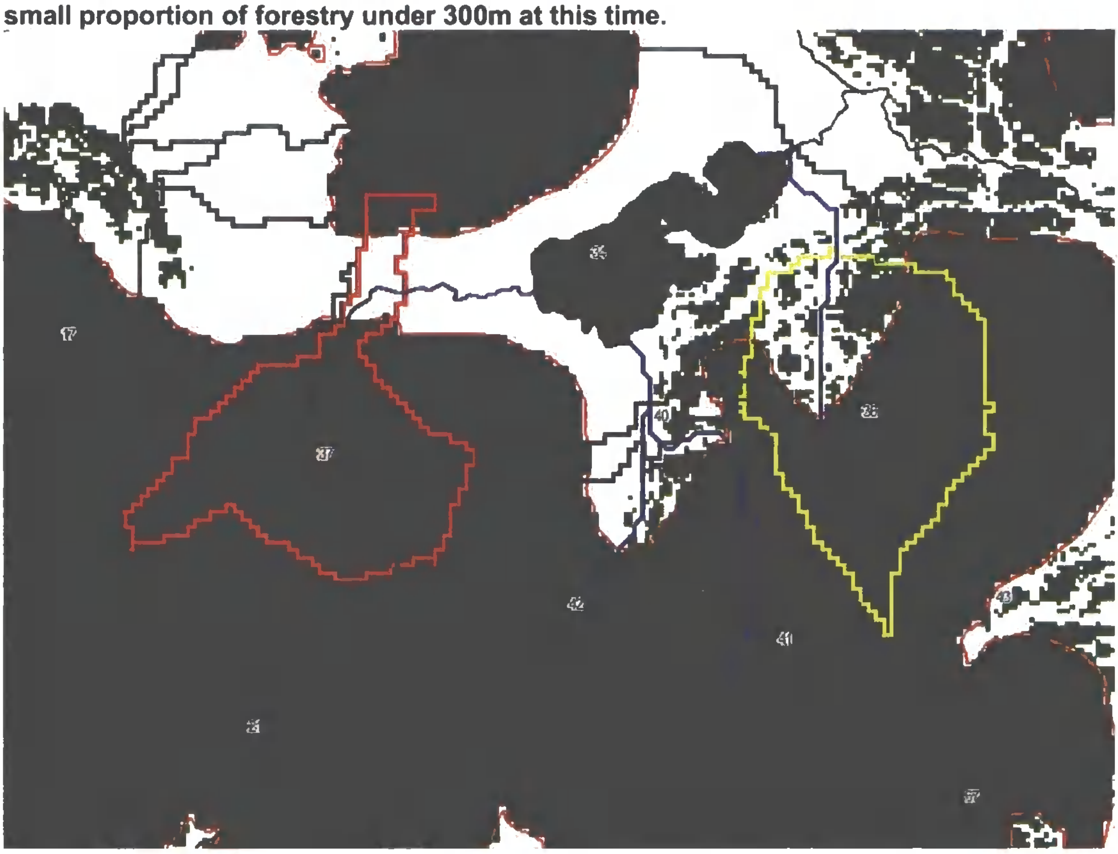
Later work at Loch Dee by Langan and Hirst (Langan and Hirst, 2004) on a longer time period of data showed a more conclusive "forest effect" indicating that "*after 1996 the Dargall Lane indicates an increase in pH and from then Green Burn shows the lowest pH*". This is matched to increasing capture of atmospheric pollutants, with declines in sulphate being greatest in the Dargall Lane site and least in the Green Burn.

Long-term studies were one of the cornerstones the Forestry Commission argument (Nisbet, 1990) who argued they were the best method of identifying a "forest effect". However, as an increase in tree growth has been matched by a decrease in pollutant loading interpretation of a "forest effect" has been complicated. The work of Langan and Hirst (2004) and Lees (1993) suggests a "forest effect" may have been identified at Loch Dee, but whether this is the accepted scavenging "forest effect", is difficult to interpret from the results. Loch Dee itself is under 300m (Figure 4-5) as is a large proportion of the forestry in the Green Burn; meaning that the detection of a "forest effect" by Lees (1993) and Langan and Hirst (2004) may well be evidence of a "forest effect" below 300m. Clearly as 300m is an arbitrary threshold and it would be foolish to over-emphasise the significance of this. The detection of a "forest effect" at Loch Dee before a significant proportion of canopy-closed forestry developed above 300m (Lees 1993) would suggest that the selection of 300m as a cut-off may not have left much buffer between at risk and not at risk. However, as Nisbet *et al.* (1995) did not detect evidence for a "forest effect" using the same data, any trend detected must be highly sensitive to data processing, making conclusions difficult to draw. The Loch Dee data after 2000 (Langan and Hirst, 2004) has not been published: it is updated in Chapter 9 : of this thesis.

The Loch Dee project was regarded with some scepticism by certain fisheries stakeholders, which minimised its effectiveness as a means of influencing viewpoints at a local scale. These stakeholders argued that the river was not representative of the worst-case scenarios found in much of Galloway, which was taken as evidence of the Forestry Commission and Solway River Purification Board being in collusion adding to the mistrust of both agencies by the fisheries bodies:

"*There was a trial done at Loch Dee – this was widely quoted ... I went and looked at it some years ago, and what struck me was that the afforested burn, although it was planted, it was full of all sorts of spaces and bits of trees hadn't grown, it wasn't typical of some of the more peaty land where you get 100% tree cover; and the other thing was it was run entirely by SEPA and The Forestry Commission, and one wonders if* *perhaps they didn't collude somewhat to produce results that were acceptable.*" (GFT-S)

Figure 4-5 Loch Dee and the 300m rule. Map highlights cover of trees > 8m in height predicted from satellite imagery following Dunford *et al.* (2007) for 1995. It highlights the small proportion of forestry under 300m at this time.



There is little evidence of collusion, and the example of Lees (1993) vs. Nisbet *et al.* (1993) to some extent demonstrates that the FC and the SRPB had different interpretations of the Loch Dee data. However, the existence of these controversies, in addition to the perceived unrepresentative nature of the site, the fact it is a paired catchment approach and the young age of the trees within it, meant that that the project provided little assistance in terms of identifying the impact-up "forest effect" perceived by fisheries stakeholders.

4.4.1d(ii) Acid Waters Monitoring Network

In the 2005 report summarising 15 years of Acid Waters Monitoring Network data Davies *et al.* (2005) indicate, whilst they also take the scientific mechanism-down approach to the "forest effect", that scavenging is not the only effect considered by the AWMN. "*Forested sites are likely to be more impacted by acidic pollutants than non-forested ones through 'scavenging' of airborne pollutants by the forest canopy (Mayer and Ulrich, 1974), increased uptake of base cations (Miller, 1988), and reduced* *availability of soil water for diluting pollutants*" (references within text also from Davies *et al. 2005*).

They support this using a paired catchment approach of 10 AWMN "forested" and "non-forested" sites to demonstrate that forest sites have higher acid anion concentrations and are more acidic (Monteith and Evans, 2000). In addition they argue that this "forest effect" may, in addition to reducing water quality, be restricting the recovery of sites from acid pollution indicating that "*of the five catchments which contain forest cover three do not show significant trends in pH or alkalinity and one a small but significant decrease in alkalinity*" (Davies *et al.*, 2005a). They stress however that forested time-series do not show "*major dissimilarities*" from those at other sites, and that "*it is possible that trends at forested sites are simply obscured by variability caused by forest growth and felling*". They argue the need for "*continued monitoring to determine the longer term impact*".

4.4.1d(iii) Helliwell et al. (2001): Recovery

The "forest effect" as a compounding factor on recovery was also identified as an issue by Helliwell *et al.* (2001) focusing on Galloway rivers the Luce, Bladnoch and Cree. This study drew on three sites from SEPA's long-term data archive and revealed that a) there was a greater negative (i.e. recovery) trend of sulphate with time in the afforested Bladnoch and the Cree catchments than the moorland Luce; b) that pH was lower in the Bladnoch and Cree than the Luce; c) that no significant ($P<0.05$) recovery in pH could be identified at any of the three sites; and d) that lime additions prior to 1976 may have offset some of the severity of acidification resulting from the combination of acid deposition and extensive afforestation.

Again, as neither the Cree nor Bladnoch have large proportions of forestry above 300m, it is possible that the effects Helliwell *et al.* are highlighting here are of a wider "forest effect". However, the paired catchment approach makes comparisons between these sites difficult to conclude from in terms of identifying a "forest effect". In addition the approach of Helliwell *et al.* raises a very important point: SEPA have been collecting data for many years, and a wide network of sites across the Galloway region is available for long-term analysis.

4.4.1d(iv) Harriman (2003)

Harriman *et al.* (2003) studied long-term trends across 37 lochs and streams across four regions of Scotland, including 16 lochs and 2 streams (Green Burn and Dargall Lane) from Galloway. They showed significant declines in non-marine sulphate for all sites. In Galloway sites, trends in moorland chloride were shown to be negative, whilst no significant trends were identified for forested sites similarly the most significant improvement in pH and alkalinity was in lochs in high elevation moorland catchments. In terms of overall acidity "*Alkalinity and pH increased more at sites where felling had taken place than at moorland or young forest sites while aggrading forest catchments appeared to be most resistant to changes in pH and alkalinity*" (Harriman *et al.*, 2003). The work of Harriman (2003) does not help to identify the possibility of a "forest effect" beyond the one currently represented in forestry policy, but it, like Helliwell *et al.* (2001) and Davies *et al.* (2005), does reinforce the importance of a long-term view of such the "forest effect", as a factor that may hamper the recovery of freshwaters

4.4.1e Factors affecting the acceptance of a wider "forest effect".

The above work shows that there is a body of evidence (Harriman *et al.*, 1987; Lees, 1995; Tervet *et al.*, 1995; Puhr *et al.*, 2000; Davies *et al.*, 2005) that shows the potential for a wider "forest effect" beyond that currently recognised by forestry policy. It is very difficult to *prove* an impact, as some either draw on paired catchment approaches (Lees, 1993; Tervet *et al.*, 1995), or do not quantify the proportions of canopy-closed forestry and high and low altitude forestry (Harriman *et al.* 1987; Puhr *et al.*, 2000). A large part of the reason for this stems from the fact that the work has been apolitical, scientific approaches attempting to identify an impact and not focussing on arbitrary limits set by policy. Of the work by authors who highlight a forest impact in areas outside of the recognised "forest effect" (Tervet *et al.* 1995; Rees and Ribbens, 1995; Helliwell, 2001) only Tervet *et al.* (1995) makes an effort to target the forest policy by arguing against the use of the Critical Loads model as a decision making tool.

Another criticism, raised by Puhr *et al.* (2000) regarding earlier work on the "forest effect" is that *forest structure*[13] is poorly represented within the literature. It is recognised that the "forest effect" worsens with increased growth to canopy closure and yet work is presented that assumes forest structural attributes based at best on the planting year of a stand. Whilst at extremes age can provide an indication of canopy closure, site specific factors can play a significant role in determining stand height. As demonstrated with regard to the work of Wright *et al.* (1979) in section 4.4.1c and the Loch Dee work in section 4.4.1d(i) inadequate determination the canopy closure status of a forest can led to different interpretations of the level of impact of the forest cover on water quality, and indeed the suitability of a site being used as the "forest site" in a paired catchment study. Puhr (1997) and Puhr and Donoghue (2000) suggest a

[13] "Forest Structure" in this thesis refers to the distribution of forest height within a catchment, usually discussed in terms of canopy closure status, where canopy closure is defined as >8m (see 6.5.1b(i)). Puhr (1997) argues that rather than focus on *forest structure* traditional studies have focussed on either forest cover or forest age which vary in terms of their "forest effect" rather than a factor related to the height of the trees, a more physically based and comparable parameter.

solution to this problem using satellite imagery to estimate forest height and thereby canopy closure. Despite the existence of this knowledge there have been few studies to adopt this approach as a means of determining forest structure for river basin planning (Dunford and Donoghue, 2007; Appendix B); the approach in terms of this project is discussed in detail in section 6.5.1b(i).

In addition to this, following the acceptance at the 1991 Darlington meeting of scavenging of airborne pollutants as the main "forest effect" the academic science moved on to investigate new areas such as national Critical Loads monitoring (CLAG Freshwaters, 1995), dynamic modelling of acidity (Cosby *et al.*, 1990), national acid water monitoring (Monteith and Evans, 2000), increases in upland DOC (Worrall and Burt, 2007) and identifying evidence for recovery from acidification (Evans *et al.*, 2001).

Whatever the causes, the end result is the same: the mechanism for the "forest effect" as conceptualised and represented in the *Forest and Water Guidelines* does not encourage changes in forest management in areas in which local Galloway stakeholders identify a "forest effect". This is a position that has remained unchanged since the introduction of the Guidelines in 1989. With no existing study focussing specifically on separating these two "forest effects" it is impossible to determine the extent forestry guidance mitigates forestry's contribution to acidification: this problem was identified as a target for further research within this thesis (see section Chapter 5 :).

Chapter 5 : Stakeholder relationships from a Galloway Perspective

5.1 Introduction

This chapter focuses on local stakeholder relationships in Galloway and how these have influenced the transfer of knowledge regarding the "forest effect". It does this in parallel with chapter 3 by taking a historical perspective of the time period 1978-2004, and drawing on stakeholder interviews and published reports. Particular attention is paid to stakeholder network (Marsh and Rhodes, 1992; Bulkeley, 2000) and the transfer of local knowledge surrounding the wider "forest effect" identified in Chapter 4 :. The chapter focuses on three themes:

1) The process by which non-FC stakeholders shown to believe in a wider "forest effect" (fisheries stakeholders and the SEPA/SRPB[14]) developed their local knowledge of the "forest effect".

2) An evaluation of the mechanisms by which both fisheries stakeholders and the environmental regulator attempted to influence forestry policy and practice.

3) The response of the Forestry Commission at both local and policy maker levels with a focus on the extent to which "hierarchical" pressures from legislation, and "professional network" pressures between stakeholders (Tenbensel, 2005) are factors influencing knowledge transfer between stakeholders.

The chapter ends with a summary of the research questions drawn from stakeholder knowledge from this, and the previous two chapters which form the targets for research for the remainder of the thesis.

5.2 Local Knowledge Formation

5.2.1 Early Warnings – Local identification of acidification

Acidification was not identified as a problem in the UK until the late 1970s (section 3.2.1b). In Galloway local stakeholder explained that they had begun to identify the impacts of acidity on water courses in advance of national recognition:

[14] In 1996 the SRPB became integrated into SEPA, and whilst this changed the focus on some aspects such as the Loch Dee project "[it] was less important to them than to the SRPB", SEPA stakeholders state that "by and large I don't think we saw much change" (SEPA-G). As a result they are treated as equivalent in the discussion that follows.

"When in the 1970s I knew the keeper of the Kelly estate, he'd been on the Fleet all of his days and it was he that warned me that these areas that had been planted just after the war were going – I don't think he described them as 'acid', but were going dead." [GFT-S]

"Just before [the CEGB's] visit [in 1978] I had to deal with an incident at a fish farm … who were having trouble getting their rainbow trout to grow, or even survive. The hatchery was fed by a tributary of the River Dee system called Lochnallie Burn and … it looked as good as any other – crystal clear water, good gravel etc. so I walked about a mile up the burn checking pools etc. and I didn't see a single fish and that alerted me that something was going on…so we took samples of the hatchery water and found that it was pretty acid " (SEPA-G).

The SRPB stakeholder indicated that the first contact that brought awareness of the larger acid-rain debate to Galloway (SEPA-G) occurred in 1978 when Gwyneth Howells of the Central Electricity Research Laboratories (CERL) visited the Solway River Purification Board asking questions regarding water quality in local fisheries. Following this meeting, the SRPB staff phoned around fisheries interests to bring the issue to their attention too (SEPA-G).

5.2.2 The "interested parties": Fisheries' Views

5.2.2a Anecdotal Evidence

Evidence from the Fisheries stakeholders, however suggests that they were, from the beginning, more concerned with the impacts of forestry than with acid rain. Acidification issue was amongst the arguments used, but sedimentation, the planting of trees too close to burns and the reduction of light were all raised as concerns as well (GFT-S). Their focus of their argument was inductive: they felt that the timings of forest planting matched the loss of fish stocks better than changes in emissions.

"If you look at the decline in salmon fisheries in the Fleet it began in the 1970s; the Cree was slightly later, lost its salmon populations in the 1980s – all this is exactly when the planting was done – this is when the fish started to diminish – particularly in areas which had been planted … Emissions were at their highest in the 1960s, and also salmon stocks had never been higher. Now how do you relate that? Since the 1960s emissions have been falling but its only in the last year or two that we have seen any improvement in the rivers." (GFT-S)

Whilst the national scale argument focussed on the relative roles of sulphate emissions and land use change (section 3.2.1b), debate in Galloway appears to have resulted from a general confusion as to the scale and significance of both acidification and the role of forestry. The Galloway Fisheries Trust report that a key problem at this stage was that all evidence of a "forest effect" from fisheries stakeholders was based on anecdotal evidence without quantitative data to support it.

"*The district salmon fisheries boards were finding a reduction in fish stocks, particularly the spring stocks and that's what really started it … they started to raise concerns and I think it was probably linked to forestry and pH, but they had no data – they didn't have anything, just a sort of feeling and at that point [both] the River Purification Board and Forestry themselves refused to have any link between the two.*" (GFT)

5.2.2b Fisheries vs. the official Forestry Commission view

The Forestry Commission's hard-line scientific stance of the time (Cf. Chapter 3) left fisheries stakeholders in a weak position for knowledge transfer. As the Forestry Commission at this time were demanding that any "forest effect" must be proven, and rejected a variety of studies performed by established scientists (e.g. paired catchment approaches, Welsh Water, AWMN: see 3.2.4) anecdotal data would not be sufficient to influence change. Furthermore, the FC stressed that the root cause of acidification was air pollution (section 3.2.2a) and not forestry. Interview evidence suggests that the different views around the existence of a "forest effect" led to significant tension and mistrust between fisheries stakeholders and the Forestry Commission particularly with the Forestry Commission Hydrologist and FC policy makers at a national level:

"*I remember at one meeting where we questioned an area which was being planted [the Forestry Commission hydrologist] told us that the planting of land in Galloway was completely unrelated to acidification – acidification was a process that was taking place anyway and that forestry had no bearing on it at all, and this was the sort of remark that caused enormous ill feeling*" (GFT-S)

"*There was a huge issue of denial from the Forestry Commission, I mean it was absolutely unbelievable the way people like [the Forestry Commission hydrologist] used to be, I saw him when he first started here where you know if you said it was black it had to be white – just argued all the time; that seemed to be his main job – total non-acceptance.*" (GFT)

This evidence is supported by the local SEPA team leader who also recognised the frictions between forestry and fisheries stakeholders: "*[The Forestry Commission Hydrologist] was very defensive to start with*", and stressed that this reflected what SEPA-G saw as "*the official FC position; they could not afford to admit liability, if you like, because of the potential compensation claims.*" (SEPA-G)

The factors that, at this time, lead to the Forestry Commission at a policy level being resistant to acknowledging a forest role in acidification prevented them viewing fisheries knowledge as relevant to them, and so being open to knowledge transfer. Chapter 3 : reveals that these factors included: i) the fact there was no accepted position at a national scale as to whether or not forestry or air pollution was the root cause of acidification, and the evidence for it being air pollution was more compelling (see section 3.2.2) and ii) the Forestry Commission's targets at this time were focused on its economic arm and thus on increasing timber reserves, with considerably less focus placed on environmental conservation (see section 3.3.3).

5.2.2c The Cree Salmon Survey 1988: quantifying the problem

In 1988, pressure from Galloway stakeholders that not only included fisheries interests but notably both the SRPB and the local Forestry Commission, led to the Department of Agriculture and Fisheries for Scotland organising a three month survey of the Cree. The completion of the survey provided fisheries stakeholders with data at a regional scale that quantified what the fisheries stakeholders had feared: it "*highlighted the apparent collapse of the High Cree salmon fishery, and produced evidence of no successful spawning and the complete absence of young salmon in a catchment once renowned for angling and regarded as a major spawning and nursery area*" (GFT, 1989; Stephen, 1988). It represented the first empirical proof that there was a dramatic impact of acidification on fish stocks within the region.

The data collected were not however sufficient to scientifically prove a "forest effect" on the fish stocks and implicate forestry as the cause that many fisheries stakeholders believed it to be: "*because of insufficient quantitative baseline information concerning the physical and chemical characteristics of the High Cree area it is difficult to determine which, if any effects can be attributed to forestry operations*" (Stephen, 1988).

Nonetheless the data were influential as it clarified that there was a real impact on fish stocks: as a direct result, local measures were put in place to ensure that more data were collected, and the West Galloway Fisheries Trust[15] was created (GFT, 1989). The GFT was independently funded initially by the four local river boards within the area (Luce, Bladnoch, Cree and Fleet, and later the Solway Dee) with additional financial contributions from Dumfries and Galloway Regional Council, the Atlantic Salmon Trust and the Salmon and Trout Association. The GFT's remit was to gather knowledge in the form of better quantitative data to establish a baseline of information concerning the scope of the problem within the region, and to set up management schemes to tackle the problems where identified.

5.2.2d Data in support of a wider "forest effect": The GFT

Since 1989, the GFT collected electrofishing and egg box data[16] to identify the extent of juvenile fish stocks within the region. By 1994, it had demonstrated that for large areas in the headwaters of the rivers Bladnoch, Cree, Cross water of Luce and Water of Fleet young salmon are not found, and in some cases no fish were identified at all (Stephen, 1994a). The trust supplemented their quantitative data with anecdotal evidence from fishermen, landowners, shepherds and poachers and confirmed that areas of the River Cree and Bladnoch where fish were lost "*used to support plenty of both trout and salmon*" (Stephen, 1994a).

Exploring the impacts of forestry was a key GFT role, and as demonstrated through their views above and in Chapter 4 they are a key proponent of the impact-up view of a wider "forest effect": section 5.3.1 discusses the approaches taken by the GFT to get their view of the environment represented in forestry policy and practice, and the factors that they identify as barriers to this knowledge transfer.

5.2.3 The Environmental Regulator: The SRPB stance

This section focuses on the way the Solway River Purification Board came to understanding of the "forest effect". It is clear that they initially found themselves in an awkward position as, despite having records of water quality for some Galloway streams that went back to the late 1950s, these records had failed to identify any increases in acidity. Data from the SRPB reports, indicates that until as late as 1977, rivers such as the Cree which in 1988 was found to be devoid of salmon (section 5.2.2c), were described as of a "*high standard*" and "*largely unaffected by the presence of man*" (Solway River Purification Board, 1977).

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[15] Later renamed the Galloway Fisheries Trust, the name which this thesis uses to refer to it.
[16] Egg-box studies use the survival rate of fertilised eggs as a measure of the suitability of freshwaters for spawning.

SEPA identify the reason for this being that the focus of their monitoring was on more traditional point-source forms of pollution such as sewage escapes, or industrial outflows:

"*Although the Solway River Purification Board had been monitoring the quality of waters in SW Scotland since the mid 1950s they had little or no evidence to confirm that water quality in certain upland areas was becoming acid, to the extent that it threatened indigenous brown trout populations. The board's river monitoring programme was focussed on the larger rivers and main tributaries where it was considered that water quality was most at risk from direct industrial and sewage discharges. There was little if any regular sampling of waters in upland catchments*" (Welsh, 1992).

The non-detection of the acidification issue was far from being the case only in Galloway, and stemmed from the fact that the River Purification Boards at a national scale saw "*remote, sparsely inhabited upland areas ... as being unpolluted*" and as a result they were monitored "*very infrequently, if at all*" (Doughty, 1989). This serves as a reminder of the importance of context in the interpretation of scientific data (section 2.2.1): an impact can only be detected and controlled if it is first identified, and for that correctly targeted monitoring is essential; this is discussed further in section 5.3.1a(i).

As a result of these monitoring concerns, when the acidification issue was identified long-term SRPB records provided little data to draw on to give them an indication of the extent of the "forest effect". To attempt to resolve the issue the SRPB involved itself in significant data gathering approaches. It widened the scope of its monitoring network (from 16 sites in 1978 to 33 in 1987); became involved in scientific research within the region such as the Loch Dee Project (4.4.1d) and performed *ad hoc* forestry/moorland paired catchment experiments searching for evidence for a "forest effect" (4.4.1c).

In 1980 the SRPB report, regarding the Cree, that "*so much of this river system is now afforested that it is felt that such a rapid and wide-spread change in land use must have an effect on water quality*". This indicates that they, like the fisheries trusts, were open to the idea of a impact-up "forest effect", from an early stage, in absence of an agreed mechanism. Section 5.3.2 discusses SEPA's role in the transfer of knowledge in support of this view within the policy network surrounding the "forest effect", both in Galloway, and in relation to SEPA's role on the *Forest and Water Guidelines* panel.

5.2.4 Forest Practice: the local Forestry Commission response

It should be noted that the strongest "*ill feeling*" (GFT-S) targeted by fisheries stakeholders at the Forestry Commission as a result of the FC's denial of a "forest effect", was targeted at the Forestry Commission at a national scale. Evidence from interview and SRPB reports indicates that the local FC, in the absence of any forestry guidance, began to adapt their management in recognition of local concerns expressed by both fisheries stakeholders and the SRPB by introducing buffer strips between their new plantings and watercourses (FC-G).

"*I think certainly there's a view that forestry's response or acknowledgement of the contribution it made wasn't very rapid – but I think at the local scale the response was a little bit quicker in terms of trying to do the right thing in the policy context they had available*" (GFT-X*)

"*To their credit the Forestry Commission has, acknowledging that problems could exist, in the south of Scotland modified planting techniques. Trees are no longer taken right up to the edge of water courses and plough furrows and drains are stopped short of natural stream channels*" (SRPB, 1982).

In doing so the Forestry Commission at a local scale demonstrated that it was willing to take a precautionary approach in the absence of scientific proof, long in advance of the precautionary principle's popularisation following the 1992 Rio conference (). In following such an approach the FC showed itself more open to outside viewpoints than Forestry Commission policy makers who continued to argue a lack of evidence for the existence of a "forest effect". In terms of the modes of governance put forward in section 2.2.1f (Tenbensel, 2005), "professional network" pressures from local stakeholders are shown to influence forestry practice in support of a precautionary response, at a time when the views of policy makers, the "hierarchical" drivers of forestry practice, are strongly opposed to any "forest effect", and there was no official policy response.

5.3 Factors affecting knowledge transfer

The previous section focused on the development of stakeholder conceptions of the "forest effect" in Galloway. It has been demonstrated that both the GFT and SEPA staff members, including the SEPA *Forest and Water Guidelines* panellist (SEPA-G), have from an early stage, conceptualised a wider "forest effect" than that seen in the current *Forest and Water Guidelines*. The following section focuses on the roles that both the GFT and SRPB/SEPA have played in terms of knowledge transfer between stakeholders within the region, particularly with regard to getting a wider "forest effect" reflected in forestry policy and practice. "Hierarchical" pressures, such as those between the *Forest and Water Guidelines* and forestry practice and between SEPA as a regulating body and the forestry practice are compared with "professional network" pressures from SEPA, the GFT and academia at large in an attempt to identify the factors that encourage and discourage knowledge transfer.

5.3.1 The "interested party": GFT and knowledge transfer

The GFT as an NGO have no official legislative power; the following section presents a selection of examples of the "*knowledge deliberation*" (Hajer, 2003) process by which the GFT have engaged with other, more influential, organisations in order to encourage their views of the "forest effect" to be realised. These examples are used to identify factors that encourage and inhibit access to knowledge.

5.3.1a Data-related factors

Interviews with the GFT reveal a number of issues surrounding data collection, interpretation and sharing which are factors that affect access to knowledge and its transfer between organisations.

5.3.1a(i) Monitoring

A first case study is provided in an example from the early years of the GFT where the GFT, having performed their own monitoring outside of the areas monitored by the SRPB claimed that the SRPB monitoring was not accurately capturing how extreme the problems of acidification really were. This led to "*significant dispute [developed] between the Fisheries Trusts and the purification board*" who did not believe the GFT results "*the Fisheries Trust had constant monitoring equipment in certain locations on catchments on the Cree, the Bladnoch and the Luce at that time, and the purification board didn't agree with those results initially ... so we worked with their technicians to bring our water quality data into the loop so that when they came around and calibrated their own equipment they ... visited ours at the same time.*" This process showed that the GFT had been correct which "*moved the debate on from that the pHs were wrong to the pHs are right and now we have a problem*" (GFT-X*).

In addition to this, the GFT also demonstrated that some of the existing long-term monitoring locations were not located in the areas where conditions were worst and that by doing so whole rivers were being misclassified "*[SRPB/SEPA] have got their long-term sites, for instance there's one on the upper Tarff ... which we used to get healthy salmon still there, but move literally 200 yards up the stream and you go* *through a geological fault, and from there, there are no fish at all... and that was their upper point and they were using it to classify the whole upper river!*" (GFT). They complain that whilst the SRPB did "*move the site up and help downgrade it*" the approach was rather *ad hoc* "*its not as if there is a system there*" (GFT).

This case study is raised here as it demonstrates two important factors regarding the transfer and access to knowledge. Firstly, the importance of methodology and context in determining the appropriateness of any scientific/ monitoring approach is stressed, following Latour and Woolgar (1979; section 2.2.1); secondly, openness to professional network pressures applied by the GFT allowed the SRPB to improve the knowledge gained from its monitoring process: by working alongside the GFT, rather than dismissing their evidence as unreasonable, greater understanding was achieved.

In influencing the SRPB the GFT aimed to encourage it to use its role as the water regulator role to influence to the Forestry Commission. The GFT argue, however, that the SRPB have never shown initiative in terms of tackling acidification. The tensions raised over data and the lack of a systematic (fisheries-based) approach to site location are included within GFT's arguments in support of this view. The issue is discussed in more detail in section (5.3.1c)

5.3.1a(ii) Factors affecting data sharing

Interviews with the GFT also identify factors surrounding data and monitoring that prove to be barriers to knowledge transfer. The GFT admit that an unwillingness of the GFT to share their raw data with outside parties has restricted their involvement in knowledge transfer "*what we've heard back from [local] forestry all the way through is that we are very poor at disseminating our information*". They identify economic reasons as a factor that has influenced this "*[poor dissemination has] not always been a mistake ... being privately collected we don't just hand out the raw data because its worth something and we have to pay*" (GFT).

Ownership and cost are not the sole factors that influence this reluctance; the GFT also stress that concerns over the way that data are interpreted are an additional factor that makes them reluctant to give their data to outside parties. They argue that without specialist local knowledge of the river system raw numbers can easily be misinterpreted "*5 parr per 100m^2, if that's all [the habitat] can take then its 100% full, its great, but another site might have 100 fish per 100m2, but if the habitat could support 2 or 3 hundred then its still a poor fish population*" (GFT) and cite a key example where they shared their data which had the inverse effect in practice, which made them wary for the future:

"*There was an obvious case a few years ago when [the second Galloway Fisheries Trust Biologist] was here and he basically got a big coloured pen... and put green lines where there was fish and red lines where there were no fish and then gave it back to the Forestry Commission and sat back and said 'this is great now they know where there are no fish, they'll try and improve those' and it turned out they did totally the opposite. They basically took it as, where there are no fish, they took it as not being sensitive and where there were fish they took it as sensitive so they basically widened the riparian zones where there were fish. And our argument was – you don't need to and ten metres [buffer zone] is fine because the water quality is good, but then they increased it to thirty ... and it's obvious in hindsight but it probably put everything back years.*" (GFT)

The points raised in this section stress the importance of social, economic and pragmatic factors in the transfer of knowledge; to achieve Best Available Knowledge around any one environmental issue considerations such as these cannot be overlooked as "*part of the process*". Furthermore, some expert knowledge may be needed to inform the debate to assure that datasets are not taken out of context.

5.3.1a(iii) The Precautionary Principle and the level of necessary proof

Another factor raised by an analysis of the GFT's approach as a barrier to knowledge transfer is the "*inexact*" nature of the science around the "forest effect", and the level of proof required to instigate change in policy and practice. In the early 1990s, the GFT fisheries scientist at the time wrote an article to the Green Highlander (Stephen, 1992 reproduced in GFT, 1992/3) which stressed that "*the question of proof raises its head time and time again*" and argued for action in the absence of proof being necessary to "*to actually achieve anything in fisheries management*":

"*We may not be able to quantify exactly how many salmon fry per square metre will be lost to a system ... by planting Sitka spruce too close to our upland burns, ... but we do know that, everything else being equal, [this is] generally bad news as far as the carrying capacity of our burns. Just because we have not been able to quantify the problems completely should not stop us from trying to dissuade foresters from planting trees too close to burns ...*".

Following this argument in support of an impact-up interpretation of the "forest effect" Stephen (1992) proposes integrated catchment management involving wider communication and knowledge transfer: "*I feel the sensible way forward for fisheries management is to introduce catchment management schemes based on cooperation between landowners [and other interested parties] ... through communication and cooperation, the goal of sensible long-term land use planning can be realised*" (GFT, 1992/3).

In reflection on this, it is worth considering the extent to which the Forestry Commission policy makers' have taken a precautionary approach. As demonstrated in Chapters 3 and 4, it is clear that the Forestry Commission policy makers' views remain strongly science-based, founded on a clear belief that the forest scavenging mechanism is well understood, appropriate to identify the areas at risk, and well represented in policy. In the 4th edition of the guidelines, however Forestry Commission policy makers refer to their actions regarding a) the use of a high flow ANC value of zero in the Critical Loads model; b) the inclusion of national Critical Loads exceedance squares adjacent to exceeded ones; c) using 1995 deposition rather than more contemporary sulphate levels; and d) including SAC catchments below 300m; as examples of a precautionary approach within the *Forest and Water Guidelines*. Whilst these approaches could of itself be criticised as precautionary only within the current understanding of the risk, the earlier editions of the Guidelines showed little evidence of any precautionary action, as demonstrated by the restocking/replanting issue (section 3.3). At the level of forest practice however there is evidence of precautionary approaches being adopted by forestry practice in advance of forestry policy (as discussed in section 5.2.4); this is discussed further in section 5.3.1b(v).

5.3.1b Influencing External Stakeholders

The following case studies focus on examples of knowledge deliberation in which the GFT have attempted to influence external parties in an attempt to transfer their understanding of the wider "forest effect".

5.3.1b(i) GFT and Academia

There is evidence in the academic literature of GFT contributing to debates in the academic literature which arguing for a change in management response to the "forest effect" (Tervet *et al.*, 1995; Puhr *et al.*, 2000 see section 4.4.1). It should be noted however that these contributions were not first authored by the Galloway Fisheries Trust and were usually performed in conjunction with other authors from other institutions such as the SRPB or the Universities of Durham or Edinburgh. Nonetheless by contributing data to these papers the GFT again attempt to put pressure on the FC to influence change in forest policy and practice. Any pressure from these papers, however, had only a limited, if any, impact on forest management policy for acidification, as the *Forest and Water Guidelines* continued and continues to reflect a view of the "forest effect" that doesn't reflect the GFT as at risk (Chapter 4 :).

5.3.1b(ii) GFT Lobbying: Cree Bank

In 1997 combined lobbying from the GFT and River Cree District Salmon Fisheries board convinced Dumfries and Galloway regional council to object to a Sitka spruce plantation of over 120 hectares at Cree Bank, which borders on the upper Cree. Before taking the objection to the council the GFT met with SEPA and the Forestry Commission but retained their objection and began lobbying the district council arguing that "*there was no consideration for balanced land use within the catchment and that the scientific methodology being used to argue why this planting was acceptable was not being used to confirm that large areas of already planted up catchment should not be replanted once felled*" (Galloway Fisheries Trust, 1996 for the River Cree).

The objections were sustained by the Dumfries and Galloway Regional Council and they formally objected to the proposals on the grounds that "*the proposal would adversely affect fisheries interests, archaeological interests and diversity of land use in the area*" (Galloway Fisheries Trust, 1996 for the River Cree). This objection was in turn sustained by the regional advisory committee "*which meant that the planting couldn't go ahead*" (GFT-X*).

This is seen by the GFT as a turning point for the Galloway Forestry Commission; "*they realised that the policy of planting trees and continuing to plant trees was not a forever policy because the objection was secured on the basis of balanced land use... and I think that was a real fundamental change because it forced the Forestry Commission to accept that firstly there wasn't a carte blanche to continue planting and also that they'd need to get a bit more of a consensual strategy deal.*" (GFT-X*)

By lobbying influential parties outside of the established SEPA-FC centred policy network who could apply "hierarchical" pressures on the FC, the GFT assured a change in forest management was initiated. The Cree Bank case study is the most significant instance prior to the Water Framework Directive where forest management practice is changed in support of the precautionary principle and the wider impact-up "forest effect". By refusing to allow planting, any potential wider effect of forestry is prevented, even though the Cree Bank area was below the 300m contour, and so would not be expected by the *Forest and Water Guidelines* to contribute significant scavenging. Lobbying is therefore a key mechanism by which views held by NGO actors outside of the government institutions have succeeded in transferring local knowledge into both forestry policy and practice.

5.3.1b(iii) GFT and the Forest and Water Guidelines consultation

An additional example of successful knowledge transfer by the GFT contributed to the consideration of Special Areas of Conservation under 300m in the *Forest and Water Guidelines'* risk-based approach. The GFT along with many other consultees were "*allowed to discuss very early on with the draft [and] gave a presentation in Edinburgh to do with some key issues ... our base concern was this 300ms issue ... at that point SACs were over 300m as well, but after our presentation they agreed to allow SACs to be any height*" (GFT). This openness on the part of the policy makers to a) consultation, and b) change, is very significant in terms of both knowledge transfer and willingness to follow the precautionary principle. However the restriction of the precautionary approach to SACs means that, areas such as the Fleet, identified by the GFT as impacted, but under 300m, would remain at risk under conditions of the wider "forest effect". It is also important to note that although SACs were included, the FC policy view is very much that a "forest effect" is unlikely in these areas (see 4.3.2).

This shows that whilst consultation is a mechanism that encourages many viewpoints to be considered; it does not necessarily remove the priority given to pragmatic and Science-based concerns over issues raised by local knowledge.

5.3.1b(iv) Working relationships with the FC

In spite of the complications of interpretation and the reluctance to share data (section 5.3.1a(ii)), evidence from interviews with both the GFT and the local Forestry Commission show that GFT have in fact used their data so that, by 2004, an open two-way dialogue with the local Forestry Commission was set up by which knowledge from the GFT is directly available to influence forest practice:

"[The FC Galloway District Manager] says 'right, you're our fisheries experts'; I get copied into letters all the time, people asking questions about fisheries and he's just said 'right the GFT, fisheries experts that we work with, and we'll do whatever they say within reason'" and as a result enables the GFT to influence management practice *"they've just cleared 150m of a wee burn out, a few trees for about eight grand, which is a bad economic loss for them but in the same way they don't expect us to say every single area"*.

The relationship is certainly two-way and knowledge of the Forestry Commission's priorities and responsibilities has transferred to the Fisheries Trust. The GFT recognise this, saying "*[we] try not to take the mickey with them*" and adding that they have learnt a lot in terms of how to compromise at the hands of the Forestry Commission "*[The FC Galloway District Manager] got us to understand very well I think is prioritising, and I fully understand we cant just demand or shouldn't, as some of the district salmon fisheries boards would, say no trees in the Fleet. We need to prioritise and have our argument and maybe understand to forestry what would help them" (GFT).*

The data-exchange relationship with the GFT is a relationship that the Forestry Commission also clearly enjoy "*GFT have provided us with data on the quality of all the streams and given us jobs to do, water gates needing renewal or overhanging trees that need addressing ... we are very often fundraising together, although we don't issue grants (that's not our purpose) we often help the GFT to get fundraising for projects, we help them with their continuous monitoring, they bought four bits of kit – we paid for two of them*".

5.3.1b(v) Local FC: Beyond the Guidelines

A key factor influencing the FC to include GFT knowledge is the change in the overall stance of the Forestry Commission to environmental conservation as reflected in the Forestry Strategy. As discussed in section 3.3.3, environmental conservation is now "*one of [their] primary roles*" and the Galloway District Manager recognises that "*this doesn't mean we don't have negative impacts ... [amongst other things] the growing of trees does affect acidity... but we're balancing this against our objectives and one of our key objectives is conservation, so that for example safeguarding the salmon population is an important objective for us and we spend a lot of money on that every year and will continue to do so.*" (FC-G)

As a result they are able to go beyond the *Forest and Water Guidelines* where this will help "*we may act on a precautionary perspective beyond the standard set by the guidelines because its so important that the Bladnoch gets its SAC – it's the last site with spring line salmon, we'll bend over backwards to make sure we get that right even though we'll spend a lot of money, lose a lot of money, we'll do that.*" He explains that whilst they have to "*follow the Guidelines as a minimum standard*" that management practice can be flexible to err on "*the side of the environment*" and that this is that they "*normally do*". The guidelines may say that "*a particular stream has got to have 20m on either side without planting*" and they might plant "*30 or 40 and not worry about it*" but they would not be able to go "*10 or 15*" (FC-G).

This flexibility was intended by the policy makers who created the guidelines. In interview they stressed that the *Forest and Water Guidelines* were designed to "*bear in mind the practicalities*" and take a "*pragmatic approach*". The guidelines do contain "*hard and fast regulations where there is a legal requirement, but where it is best practice only that is also made clear that there is an element of room for negotiation*" (FC-PP). It should be noted here, that whilst the fact that the option to go "beyond the Guidelines" is recognised by the stakeholders interviewed here, Chapter 7 presents evidence that Forest Conservators, who need to legitimise their decisions to private forest companies do not have the same flexibility and closely follow a more literal interpretation of the Guidelines.

The openness of the current Forest District Manager is seen as a factor influencing knowledge transfer; FC-G is well regarded and both SEPA and the GFT who highlight him as a key player who instigated a "*sea-change*" in terms of the Forestry Commission approach to environmental issues (GFT, SEPA-G, GFT-X*). It is recognised, however, that the flexibility in terms of "*a willingness to do what is possible*" was present on the part of the local Forestry Commission even in the past when "*there was great dispute and friction*" (GFT-X*) (see also section 5.2.4).

5.3.1b(vi) Limits to FC practice

Despite this flexibility, and the openness to knowledge transfer it exemplifies, the FC Galloway District manager does make it clear that there are limits to the extent that forest practice can be modified, giving an example of an old style drain flowing directly into a water course, "*the GFT will work with us and if we can identify a simple way to do something, say with a spade, it will be done, either the GFT will do it or we will do it ... but in many cases that is not actually possible ... and the whole area needs to be redesigned and to do that there would need to be a major job like felling and restocking*" and "*what we are not going to do is fell whole areas prematurely*" (FC-G). In doing so he reveals that economic concerns remain a key factor modifying the extent that forest practice can integrate external knowledges, a factor not explicitly recognised in the science-based approach of the *Forest and Water Guidelines*; this is further discussed below with reference to SEPA (5.3.2e).

5.3.1c The GFT and SEPA

The data-exchange relationship between the GFT and the local Forestry Commission means that the FC have access to fisheries data in a way that SEPA do not. "*We[, the GFT,] see fisheries data, and so do forestry themselves [the FC Galloway District*

Manager] is always keen to get fisheries data as one of the main parameters. And SEPA don't have that and they don't seem to be able to adapt and I don't understand why." (GFT)

In fact, an interpretation of the GFT's interview data suggests that from a GFT perspective SEPA themselves are a potential barrier to knowledge: as an NGO the GFT have no legal powers, as a result, SEPA and its predecessor the SRPB have been key institutions that the GFT have targeted for lobbying in an attempt to get their view of the environment represented in policy. As a member of the *Forest and Water Guidelines* panel, SEPA has the power to influence the policy response. As the GFT do not see the *Forest and Water Guidelines* recognising the problems in Galloway it is quite critical of the role of SEPA, who despite sharing a view of the wider "forest effect" (see 4.3.3b) are not seen to have put sufficient pressure on the FC to change its guidance (Cf. 4.3.1). The GFT view follows; SEPA's counterpoint is presented separately in section 5.3.2.

5.3.1c(i) SEPA as Insular

The Fisheries Trust also criticise SEPA for being very insular "*SEPA as an organisation has really never done consultations*" and that whilst the GFT admit that they have been "copied into things" for comment "*there's not been an effort to try and say 'right we're in the lead we need to sit down and work it out*". The GFT stress that SEPA have "*always very much charged on themselves*" and "*they seem far more 'in-house', and its sort of a problem because they don't have any fisheries expertise ... and they haven't really gone out and sort of brought in this expertise*"

5.3.1c(ii) SEPA have not taken the lead

The GFT argument is that SEPA have never "*taken any great lead*" with regard to acidification, saying "*we've been quite disappointed that although they seem to address really well point source pollution, the diffuse – particularly acidification, they just don't seem to have got to grips with*" (GFT). They argue that although acidification is "*not big pollution for Scotland*" it is "*a huge issue*" for Galloway, and that rather than targeting it as a special local concern SEPA have tried to use the "*same systems that they use everywhere*" to "*sort of adapt it in*". The GFT have been campaigning to get a "*forestry officer*" put in place to go out and monitor forest practice because they do not think the Forestry Commission should be allowed to monitor itself, however: " *[SEPA] have said 'we'll try and keep an eye, but farm pollution comes first', which means when it gets busy nobody gets out to keep an eye on forestry ... and if you take Dumfries and Galloway and south Ayrshire it's a huge area a massive land use*" (GFT).

5.3.1c(iii) SEPA don't have the specialist skills

A further criticism is that the GFT see SEPA as lacking the specialist skills to fully participate in discussions over the "forest effect", and water management in general. They argue that anyone with a specialism in practical water management would be valuable and stress that some of the advice given by SEPA, regarding silt traps that were "*six times the size of a car*" were "*ludicrous*" and "*probably caused more erosion because of the way the sides were built than the wee burn was causing from the road ... and Forestry were really annoyed because basically their engineers were far more experienced and it showed*" (GFT). They particularly criticise SEPA for lacking an experienced chemist with which to argue with the Forestry Commission complaining that in the absence of this "*everybody relates back to [the Forestry Commission Hydrologist] and you can't get away from the fact that [he] is paid by forestry, and if SEPA are taking advice from that its ludicrous*" (GFT). The following section (5.3.2) presents SEPA's view and its defence and justification against these claims.

5.3.2 The Environmental Regulation: SRPB/SEPA's view

As indicated above the GFT criticise the SRPB and SEPA of a) failing to take the lead regarding the "forest effect" and b) taking an insular approach and refusing collaboration with outside bodies (specifically, the GFT) and c) lacking the specialist skills to address the "forest effect". This section presents SEPA's perspective as a means to evaluate these claims and identify the extent to which SEPA's approach influences knowledge transfer to policy and practice.

5.3.2a SRPB and Practice

The SRPB's powers, granted it by the Control of Pollution Act (1974), were to intervene whenever a land-use contributed to an environmental pollution event. As discussed in section 1.3.1, this Act focused far more on point-source rather than diffuse pollution. As a result, the SRPB's legal powers over forestry were constrained to issues when forest actions led to specific pollution events. Nonetheless, the SRPB were quite influential in terms of modifying forestry practice by ensuring that the *Forest and Water Guidelines* were adhered to by forest practitioners as the following example from 1990 demonstrates.

In 1990 two sedimentation incidents on the Palnure Burn in the river Cree were brought to the attention of the SRPB by the GFT (Galloway Fisheries Trust, 1990). The SRPB then "*took samples with a view to prosecution, but we didn't actually take them to court, and because of that sort of pressure their methods actually improved*" (SRPB-G). The Private Forestry Company were told that "*unless suitable provisions were made to* *extract timber in a responsible manner the operation would be declared an illegal fell*" (Galloway Fisheries Trust, 1990) whilst the "*Forestry Commission took a very strong view of their mistakes and disciplined three of their staff*" (Galloway Fisheries Trust, 1990). As a result of incidences like this the Forestry Commission increased knowledge transfer within their own organisation and began training their staff in the logic behind the *Forest and Water Guidelines* and gave them power to modify their own practice if they believed their actions would lead to the guidelines being contravened:

"*They actually started teaching the guys on the ground who were doing the actual damage – the digger drivers, the 4 wheel drivers and the harvesters. The chiefs of the Forestry Commission actually gave the guys on the ground the right to stop working because they felt that there was a problem in terms of harvesting and so they called people out and then they asked us to walk over areas*" (SEPA-G).

This result, demonstrates that the SRPB were relatively effective at modifying forest practice with regard to issues of point-source pollution, and that they were good at ensuring that the *Forest and Water Guidelines* were followed; this is a fact that the GFT are willing to recognise in 5.3.1c. In this sense they ensured that knowledge was effectively transferred along the lines of existing hierarchy and encouraged practice to well reflect policy.

5.3.2b SEPA/SRPB and the wider "forest effect"

In addition it is clear from interviews that the views of individuals within SEPA were far broader than the pure mechanism-down "forest effect" of the *Forest and Water Guidelines*. The SEPA *Forest and Water Guidelines* panellist shares the GFT view that forestry is contributes to wider water quality problems, "*I've always said that there's nothing positive conifers do for water; nothing whatsoever and I'll stand by that to my dying day*" (SEPA-G). Regarding the fourth edition the SEPA *Forest and Water Guidelines* panellist continued to express doubts over the application of the Critical Loads model (section 4.3.1) and showed an agreement with the Fisheries Trust that the problem of forestry was more widespread and that the 300m rule was not the best approach to address it (section 4.3.2). As such the SEPA panellist demonstrates themselves to conceptualise the issues more following the impact-up view than the mechanism-down view.

A similar stance is also clear from the SRPB's reports. It is shown that whilst on the panel influencing the *Forest and Water Guidelines* they disputed a number of the regulations which came into practice including the forestry commissions ability to restock without consultation "*the board wishes to acknowledge the value in its being consulted on new planting proposals but wishes such consultation to apply to replanting schemes in order that past mistakes are not repeated particularly in relation to proposals in areas of acidified surface water*" (Solway River Purification Board, 1993/4) the second edition's guidance for acidification: "*the board has been very concerned with the sections relating to acidification issues and will be seeking amendments to the Guidelines during the full and detailed review that is taking place*" (Solway River Purification Board, 1991/2) and the use of Critical Loads exceedance at a catchment scale "*whilst the concept of Critical Loads is excellent, the means to implement the ideas remains far from straightforward*" (Solway River Purification Board, 1993/4).

The SRPB contributed to a number of academic papers which also query the decisions made in the guidelines, most notably in Tervet *et al.* (1995) where they argue that the Critical Loads approach is inappropriate for use at a catchment scale and Rees and Ribbens (1995) where they argue for impacts in the Bladnoch resulting from afforestation. Indeed, of the articles identified in section 5.3.1b by which the Galloway Fisheries Trust contributed to the academic debate the SRPB/SEPA were lead author on two (Rees and Ribbens, 1995; Tervet *et al.*, 1995), and also included as a member on the third (Puhr *et al.*, 2000). In addition SRPB authored Lees (1993) argued for a "forest effect" in the Loch Dee data in the face of the Forestry Commission's interpretation of the same data showing no effect (4.4.1d(i)).

5.3.2c "A jointly badged document?": SRPB influence on the F&WGs.

As the SRPB/SEPA are relatively strongly entrenched in the impact-up view of a wider "forest effect" this raises the question of the extent to which the *Forest and Water Guidelines* are truly a "jointly badged document" as suggested by the Forestry Commission in section 3.1.2b. Despite the SRPB/SEPA expressing views in print against both the use of the Critical Loads model and the restocking rule, the *Forest and Water Guidelines* continued to reflect these elements.

Part of the reason for this appears to stem back to the fact that full understanding of the science used to support the *Forest and Water Guidelines*, and the Critical Loads model in particular, is centralised within the Forestry Commission at a policy maker level. The SEPA *Forest and Water Guidelines* panellist disagreed with the use of the model and admitted to lacking the statistical and chemical skills to "*demolish it scientifically*" (SEPA-G, see section 4.3.1). Without these specialist skills the hard-line science-based approach is hard for non-specialist stakeholders to argue against; in terms of encouraging knowledge transfer between SEPA and FC policy, the GTF criticism of the need for a specialist scientist is justified.

The Forestry Commission at a local level also recognise the role given by SEPA to the Forestry Commission Hydrologist their response to the question *"to what extent do you see SEPA as having led the way towards dealing with acidification in Galloway?"* the FC reply was "*Um, I don't know really; this is not a criticism of SEPA, the way they have handled it is with the experts – who can deal with Critical Loads assessments? It's [the forestry commission hydrologist] and they have used [him] – 'here sort this out for us', conceptually and intellectually*" (FC-G). They are keen to stress that it does not mean that the Forestry Commission Hydrologist will have had an "*easy time*" and that he "*is sure that SEPA criticise him from time to time and he has to be very careful about what he says ... it's a teamwork thing and I think although the [Forestry Commission Hydrologist] has led it there has been a lot of interaction.*" SEPA have a similar view and dispute the extent to which knowledge transfer from SEPA is necessary, as the FC has environmental responsibilities in its own right, this is discussed in more depth in the following section (5.3.2d).

5.3.2d SEPA and the FC: Sister Agencies

Whilst SRPB/SEPA representatives may share similar conceptualisations of the areal extent of the "forest effect" with the Galloway Fisheries Trust, they are a public body in the same way as the Forestry Commission. Stakeholder interviews reveal that in the past the amount to which the SRPB was able to speak out against forest practice was modified by the fact that *"[the FC and the SRPB] were both paid from the public purse"* and that *"it never looks good if [they] are seen [to be] differing"* (SEPA-G) limited the extent to which the SRPB could be seen to criticise the Forestry Commission. They point out that as *"free agents"* the Galloway Fisheries Trust were in a better position to do this.

"*The thing about the Fisheries Trusts is that they were free agents – they could say what they liked about the data they obtained – some of it was a bit outrageous, but by and large they were a real thorn in the flesh of the Forestry Commission. At times I was even told to by my boss to modulate some of the things I was saying. He suggested that if I wanted to say anything I should write a paper*" (SEPA-G).

The fact that they are sister-agencies continues to play a role and neither the Forestry Commission nor SEPA regard the centralisation of knowledge (discussed in 5.3.2c) regarding afforestation within the Forestry Commission with the same mistrust that the

Galloway Fisheries Trust does. They explain that they are "*both government bodies*" (FC-G) and that SEPA's involvement in forest regulation is in their consultation for the *Forest and Water Guidelines*: "*[SEPA doesn't] regulate the forestry industry – only in so far as they deal with pollution or effect pollution issues. So the [Forestry Commission] actually regulates the forestry sector via the Forest and Water Guidelines …our policy has been that the Forest and Water Guidelines are built into the authorisations and licences for forestry activities, we're pretty content with those and we've been involved with each revision of the Forest and Water Guidelines to make sure from our position they improve each time*" (SEPA-WFD). Thus, as long as the *Forest and Water Guidelines* are followed, SEPA have little influence over forest practice.

SEPA see their approach as having been to support the Forestry Commission in self-regulation rather than to take control. This is recognised by the FC who stress that they are only a minor polluter on the grand scheme of things: "*at the end of the day from a SEPA point of view we could be another industry, we could be nuclear power, or the coal industry … wouldn't it be far more advantageous to get the industry to commit rather than forcing the industry to do something which might be impractical or not enough?*" (FC-G)

Nonetheless it is impossible to completely ignore the GFT's criticisms over SEPA not taking the lead. It was by allowing the Forestry Commission to regulate itself that the restocking/replanting rule entered into Guidance and prevented the *Forest and Water Guidelines* applying to any large part of Galloway (as demonstrated in section 3.3). Furthermore by allowing the *Forest and Water Guidelines* to include the 300m rule and the critical load model they are allowing their approach to regulating water quality to fail to highlight areas that SEPA itself has highlighted as at risk such as the Bladnoch and the Cree discussed in Tervet *et al.* (1995).

Institutional relationships therefore appear to be a factor that restricts effective knowledge transfer between the SEPA and the Forestry Commission at a policy level. Whilst this is not viewed as a problem by the government bodies involved it reduces the effectiveness of any knowledge transfer from NGO lobbying targeted at the environmental regulator, and restricts the extent to which the *Forest and Water Guidelines* reflect SEPA's own knowledge of the freshwater environment.

5.3.2e SEPA and the Common Pool Resource issue

SEPA also see the complexity of the common pool resource issue surrounding the "forest effect" and recognise the limits within which the Forestry Commission is capable of adapting their practice. SEPA-WFD* stresses that there is "*no magic wand*" for the problems of acidification, and that the FC Galloway District manager "*can't give [the GFT] everything even if he wanted to*" (SEPA-WFD*). Furthermore they stress that there is little evidence that removing trees will necessarily solve the problems of acidification "*I don't think anyone hand on heart could say 'if you take these trees out you'll have a biological response within whatever timescale*" (SEPA-WFD*), indicating that any remedial action would necessarily be precautionary.

SEPA underline the need to balance the perceived environmental benefits with the economic costs of the remedial action "*when it comes down to it, in a place like Dumfries and Galloway, where the option of removing huge tracts of forestry ... to generate, even in the hay-day of these rivers, 1,2,3,4,5 FT employment positions and sacrificing a forestry industry on the back of that – that debate is not going to win*" (SEPA-WFD*), and argue that ultimately the decision to afforest is a political one, and that if that is to the detriment of fisheries, to some extent, so be it: "*the decision of fish and trees is a political one and the environment argument is well proven that if you have trees in certain areas its going to be to the detriment of fishery – so, do you want trees? – do you want fish? The government want trees.*" (SEPA-G)

These wider economic and social factors are also recognised by the GFT who accept them saying: "*we fight the case for the fish but [in face of] the number of jobs related to forestry, the community etc. etc. all we can do is say, this is what we think for the fish, in a way if its decided that the fish are not as important as 200 jobs within the forestry... its all about the trees being in the right places*".

This recognition of the wider complexity of the economic, social and political issues is not transparently addressed within the *Forest and Water Guidelines*. By addressing the "forest effect" as an environmental science issue, with an environmental science answer provided by the Critical Loads test, the *Forest and Water Guidelines* restricts the flexibility of environmental managers to take these equally significant drivers into consideration. Furthermore the lack of transparency involved in a simple environmental risk based approach makes it unclear the extent to which wider these political, social, economic and even wider environmental considerations play a part in the inclusion/exclusion of knowledge within the decision making process. It is however highly improbable that they do not. This is made clear by considering a theoretical situation where the Critical Loads model was discovered to fail for the whole of the Galloway (as feared by the FC in section 4.3.1b) supports this; under these conditions policy makers would surely reconsider the science-based policy response and adapt to take the social, economic and political impacts into consideration, rather than felling the forest until it was 30% of its size to the detriment of the Galloway's forest industry.

5.3.2f SEPA and the WFD

The introduction of the WFD placed additional responsibility placed on SEPA, which they see as "*good news ... but BIG news as well, in terms of the number of people who are involved in it, the difficulties and the challenges*". They emphasise the need for a pragmatic approach arguing the importance of compromise to what is practical. They state that they cannot put "*contributions in the programme of measures that we're not delivering unless we've got people signed up to deliver them*" stating that "*its less an aspirational plan – the river basin plan is much more 'these are the agreed positions that we are going to implement'*". As a result, in terms of forest management they cannot impact dramatic change without a) agreements in place to instigate that change and b) ensuring that that change is proportionate in terms of cost and feasibility. They illustrate this with an example of the river Fleet in Galloway:
"*taking an extreme example of us putting somewhere in the [WFD river basin plan] for the Fleet 'there is a body at risk in the fleet, its caused by acidification and the appropriate measure is that we must chop down all the trees*'" they stress that this is something they would not be able to do because "*firstly [SEPA] can't chop them down*" and secondly its not a "*feasible approach proportionate to the problem*".

Instead they suggest that "*what is much more likely is that SEPA and the Forestry Commission and others with an interest will sit down and think about what is possible, what they can agree to, when they can agree to do it and the extent of the response that the agree is going to be targeted.*" This leads them on to stress that the Water Framework Directive "will help" the issue of acidification but that there is "*no magic wand*", and that it isn't either the Water Framework Directive or the *Forest and Water Guidelines*.

Their view of the 2015 guideline is that "*2015 is the default objective, but the reality of it is that the basin plan can set timescales which are up to two further plan cycles ahead, so you've got from 2015 to 2021 and 2027 to achieve whatever standard you set, and you've got opportunities to set less stringent objectives – so if attaining good status by 2015 is not going to be possible you can either say we'll achieve lesser status by 2015 or a lesser status by 2021 so there is a whole matrix of environmental objectives.*" They stress that "*were not living in a world where the environment is number one priority in all occasions*" and that the WFD has built in "*reality checks*" that test if the planned measures are "*disproportionately expensive*", not "*technically feasible*" or against "*sustainable development*".

These options are seen by the GFT as 'get-out-clauses' that "*dilute*" (GFT) the impact that the WFD might have had. The GFT also query what "*additional benefits*" the WFD brings stating that "*the Forest and Water Guidelines [already] address the forestry issue*" (GFT). Many other stakeholders concur that the *Forest and Water Guidelines* have been little influenced by the introduction of the WFD and that the changes within them were "*just a further step*" (FCH) that would have happened anyway (GFT).

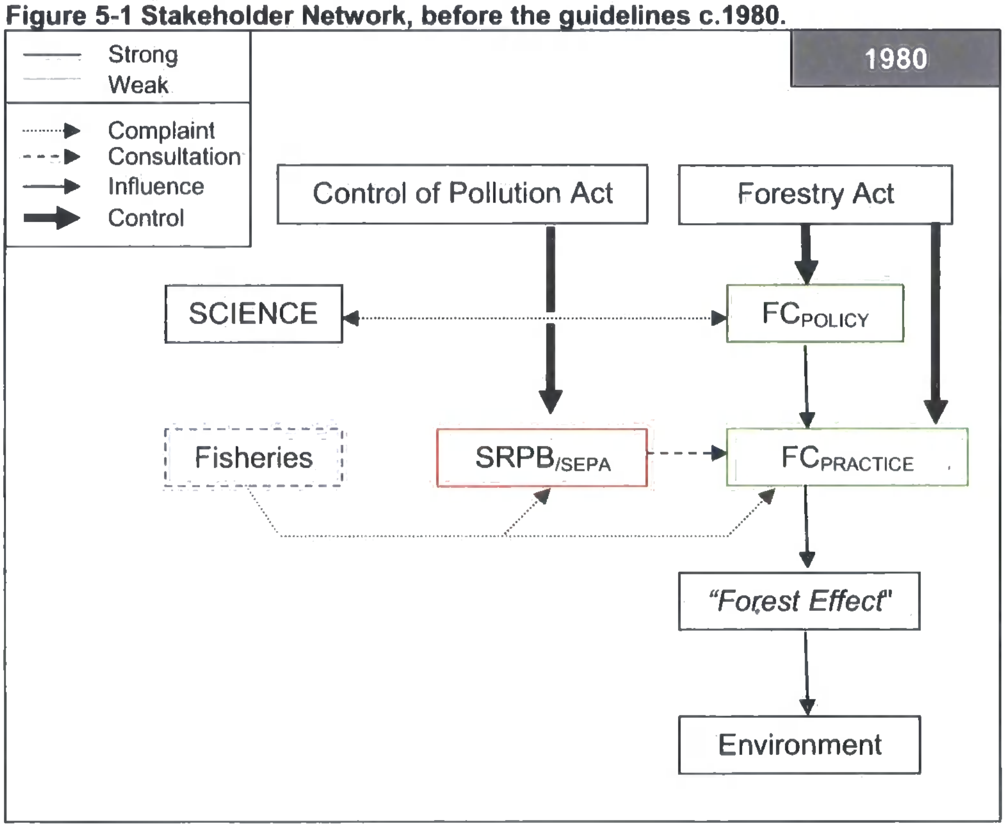
These factors suggest that the power of institutions to interpret the WFD has meant that, rather than being an "exogenous shock" from outside the system instigating policy change (following Jordan and Greenway, 1998), with regard to acidification, the WFD has the potential to be incorporated into existing structures without significant changes being made. As a result the 4th edition of the guidance in the *Forest and Water Guidelines* has changed little in terms of its approach to acidification and, as such, the WFD has not proved a significant factor directly influencing the FC policy response. It should be noted that at the time of the interviews (early 2005) the WFD was relatively new, and its impacts in practice were unclear: there is evidence in chapter 7 of the SEPA–NS drawing on the WFD as a means to encourage action beyond the *Forest and Water Guidelines* (see section7.3.1). The point is not therefore that the WFD has no role to play, but that the extent to which this role influences policy and practice is strongly influenced by the organisation interpreting the policy.

5.4 Changing relationships through time

The following section summarises the discussion above with an interpretation of the changing relationships around the policy network (Hajer, 1995a). The network is conceptualised as a series of inter-stakeholder links that enable and constrain the transfer of knowledge. The strength of these relationships change with time and are presented for four time periods i) c.1980, before the *Forest and Water Guidelines*; ii) c.1989, during the 1st edition of the guidelines iii) c.1996, during the 2nd/3rd editions and iv) c.2004, at the introduction of the 4th edition, an the start of this thesis. Below, "Science" is used to refer to the academic community at large, with the debate between Science and FC_{POLICY} being that discussed in Chapter 3.

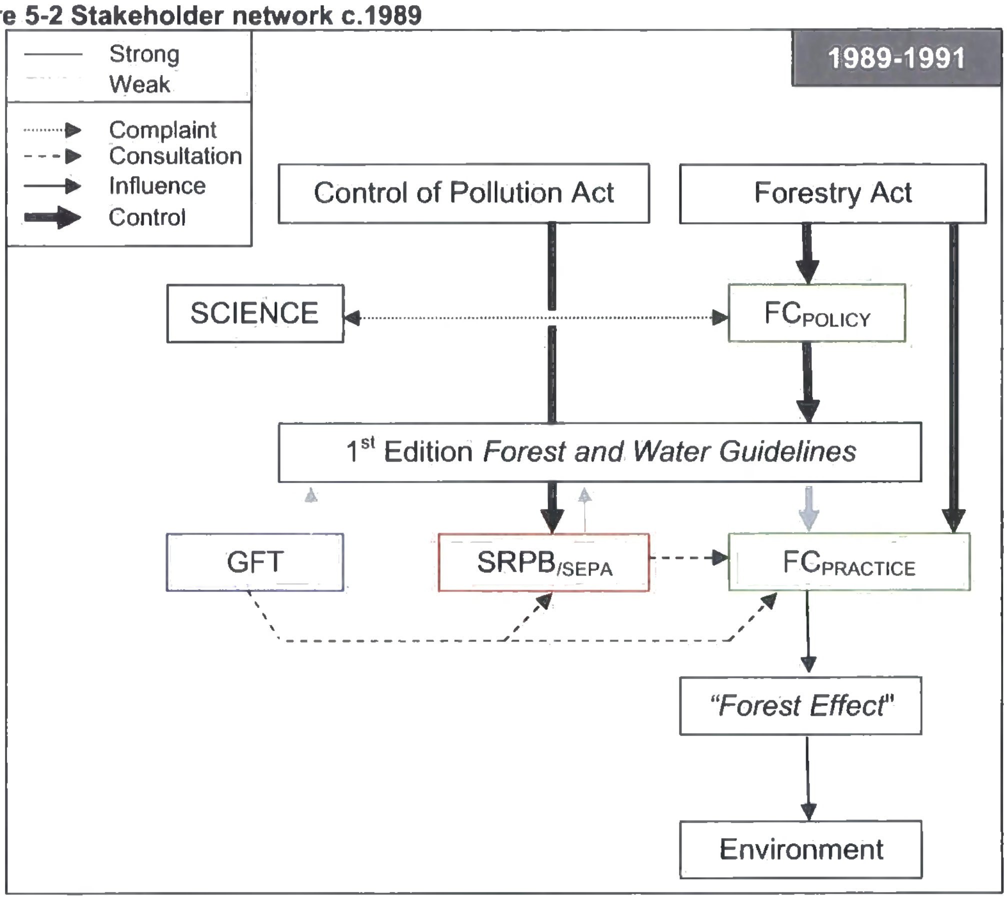
Before 1989 (Figure 5-1), there is no agreement regarding the "forest effect" between the FC_{POLICY} and SCIENCE. As a result there are no *Forest and Water Guidelines* and $FC_{PRACTICE}$ is controlled by the Forestry Act. Local fisheries stakeholders only have anecdotal data and so can only complain to the SRPB and $FC_{PRACTICE}$ drawing on anecdotal evidence. The SRPB likewise have little data and so can also only register complaint, they do however have the additional powers of the Control of Pollution Act (Scotland) and so can affect practice where point-source pollution episodes take place but they have no significant powers beyond this to tackle diffuse pollutants such as acidification. The greatest influence on forestry policy and practice during this period is, therefore, the Forestry Act, which at this time was still strongly focused on forest industry. Nonetheless, $FC_{PRACTICE}$ shows itself to be willing to respond to local pressures and agrees to take a precautionary approach by keeping planting back from burn sides.

Figure 5-1 Stakeholder Network, before the guidelines c.1980.



By 1989 (Figure 5-2) sees the introduction of the *Forest and Water Guidelines* and the consolidation of fisheries knowledge into the GFT. The *Forest and Water Guidelines* change $FC_{PRACTICE}$ in terms of providing a transparent methodological approach for dealing with water issues. The *Forest and Water Guidelines* also reinforces the position of the SRPB within the policy network; the SRPB consult on the Guidance, and use the *Forest and Water Guidelines* as regulation providing them with a mechanism to influence management practice particularly regarding sediment issues. In terms of the "forest effect", however, the SRPB's influence on the guidelines is not significant enough to remove the restocking/replanting rule, despite their objections in their own reports. This minimises the effectiveness of both SEPA and any knowledge transfer the GFT apply to SEPA. The lack of an "*agreed position*" prevents the *Forest and Water Guidelines* taking a stance on acidification (section 3.2.6. The forestry act remains the most powerful driver over both FC_{POLICY} and $FC_{PRACTICE}$.

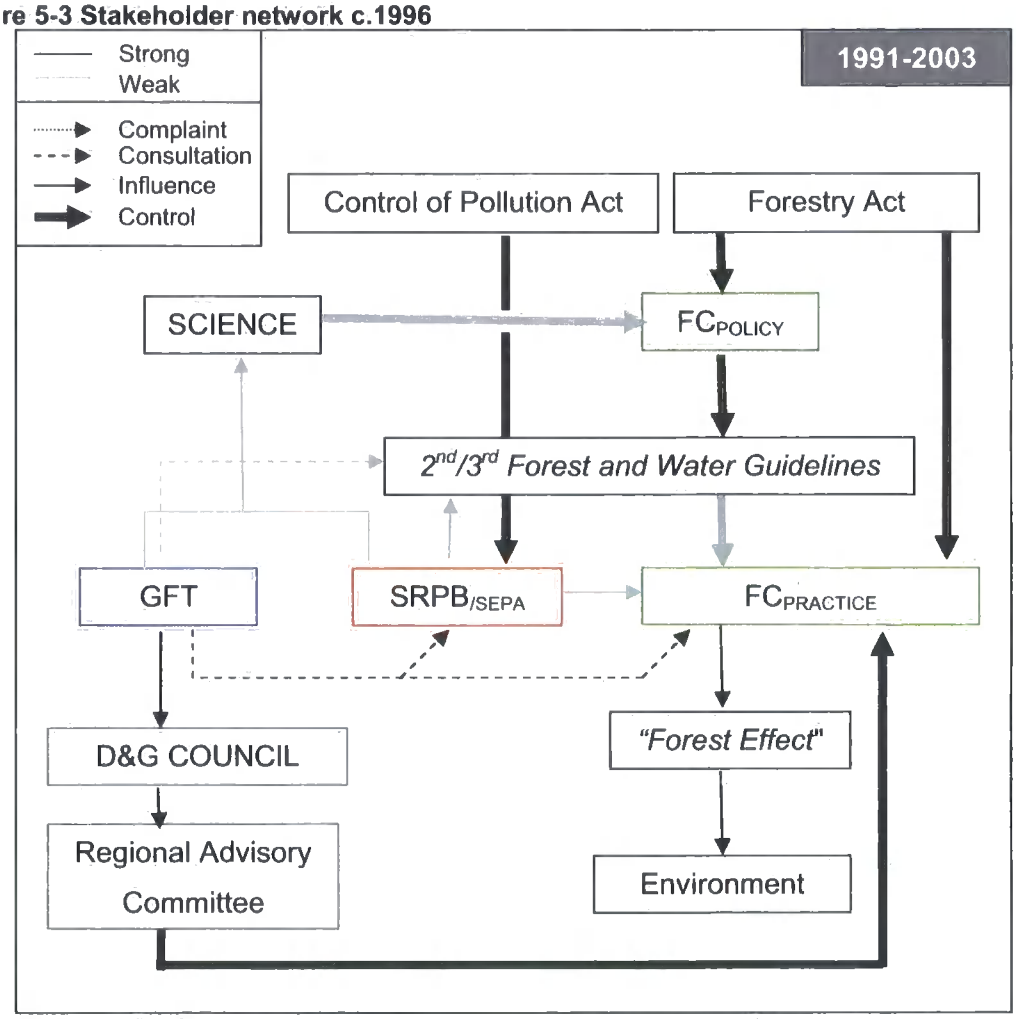
Figure 5-2 Stakeholder network c.1989



Circa 1996 (Figure 5-3), the situation has not dramatically changed in Galloway despite the introduction of the 2nd and 3rd editions of the *Forest and Water Guidelines*, due to the restocking/replanting rule preventing the *Forest and Water Guidelines* contributing to management change. As the SRPB/SEPA's main contribution to regulating the Forestry Commission is through these Guidelines, their contribution to knowledge-transfer regarding the "forest effect" through institutional channels, is also neutralised.

Instead, alternative mechanisms of knowledge-transfer are explored as a result and both the SRPB and GFT publish academic papers in an attempt to influence SCIENCE. SCIENCE is now a major driver of FC_{POLICY} following the agreement of scavenging at the Darlington meeting; however, the science regarding a wider "forest effect" (see 4.4) is not reflected within the *Forest and Water Guidelines*. Figure 5-3 also highlights that by influencing an organisation outside of the *Forest and Water Guidelines*-based policy network, the GFT placed pressure on $FC_{PRACTICE}$ at a local level in order to ensure that their view of the environment was reflected in practice during the Cree bank incident.

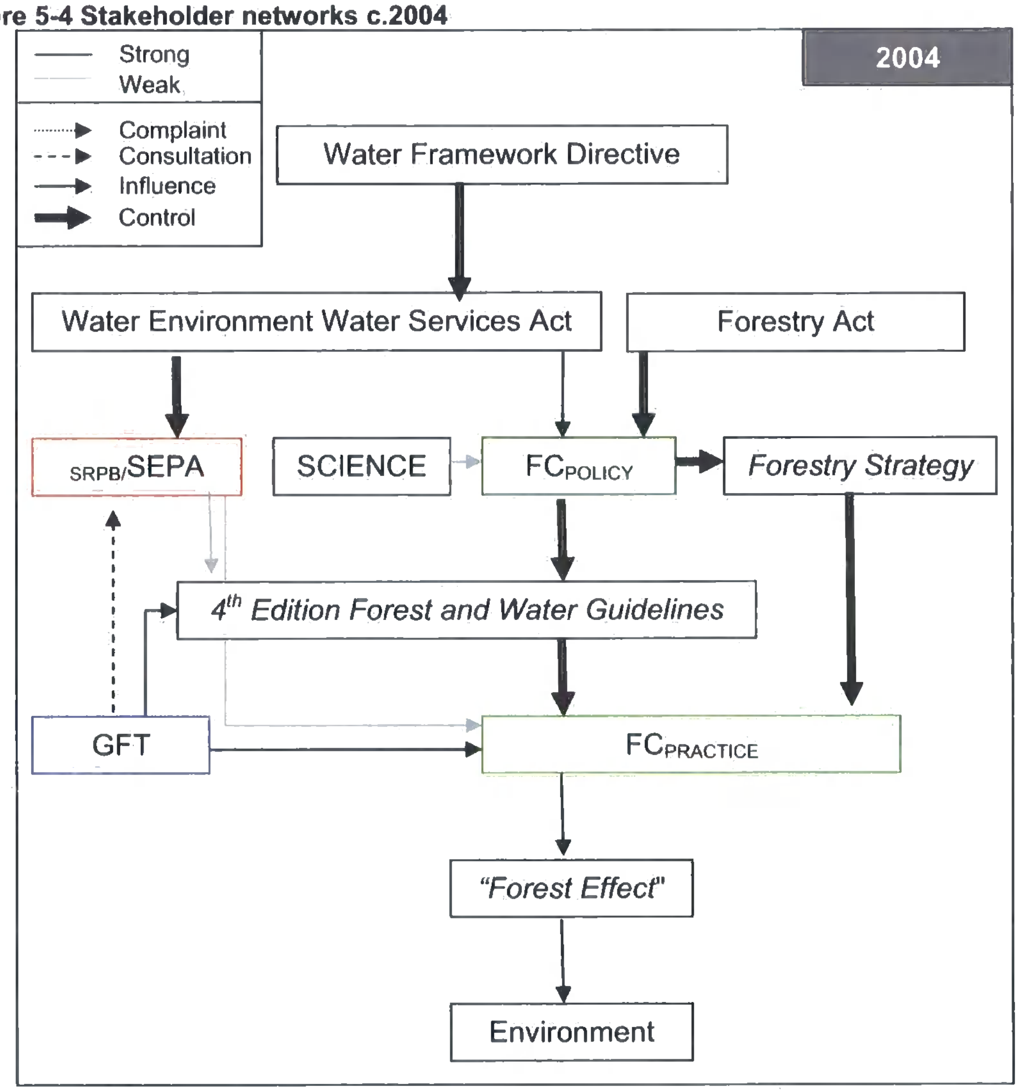
Figure 5-3 Stakeholder network c.1996



By 2004 (Figure 5-4), the policy network has shifted in response of both the introduction of the Water Framework Directive and the Forestry Strategy. Through the WFD's drive to "good ecological status" SEPA are given overall management responsibility for addressing the "forest effect". The *Forest and Water Guidelines* remain the mechanism by which SEPA see this being achieved in practice. As a result of institutional pressures and the complexities of multiple resource management SEPA has let the Forestry Commission self-regulate and as a result the *Forest and Water Guidelines* remain more strongly guided by the Forestry Commission and reflect their view of a mechanism-down "forest effect" in place of the impact-up view seen by SEPA and the GFT. The GFT continue to play a role, and through the consultation process surrounding the 4th edition contributes to the consideration of SAC areas below 300m. Furthermore, by developing a data sharing relationship with the FC they contribute directly to management practice in support of their view of the "forest effect" with wider streamside buffers being left in areas they identify as at risk. The *Forest and Water*

Guidelines and the Forestry Strategy still remain the major drivers over forestry practice and limit the extent to which forest practice can incorporate views of a "forest effect" outside of the areas identified by the mechanism-down view incorporated within the guidelines.

Figure 5-4 Stakeholder networks c.2004



5.5 Discussion

This chapter applies a discourse-coalition Network Theory approach (Hajer, 1995; see Section .2.1e) to the policy process surrounding the "forest effect". This approach was developed as a mechanism to understand the structures by which the policy process takes place (Marsh and Rhodes, 1992). It is conceptualised as "*a meso-level concept, which attempts to describe and analyse the relations between different actors, decisions, institutions, and structures and the affects that these have on policy outcomes*" (Bulkeley, 2000). In this system a policy network is constituted from the "*pattern of resource inter dependencies between policy actors*" (Smith, 1997). In the case of the "forest effect" the resource interdependencies are those surrounding the water environment; Forestry Commission activities impact it, SEPA have the responsibility to manage it and the GFT represent stakeholders who are reliant on it.

Network theory's origins are at the scale of international relations mainly focussing on the role of international scientific communities or nation states as they bargain for international agreements (O'Riordan and Jordan, 1996; Jordan and Greenaway, 1998; Sabatier, 1998). More recent work has seen the theory brought to focus on domestic policy processes as a means to consider the relationships between organisations across national/international scales (Bulkeley, 2000; Hajer, 2003). In this project the approach is applied across local and national scales as a means to identify the role of "knowledge deliberation" (Hajer, 2003; see section 2.1e) within the policy network surrounding the "forest effect". The analysis above focuses on the mechanisms by which the transfer of local beliefs surrounding the "forest effect", and later the wider "forest effect" come into existence (section 5.2) and are then "deliberated" (section 5.3-4) by those within the network. This use of the policy network concept as a means to investigate the processes by which local knowledges are included and excluded from the policy making process follows Hajer's (2003) call for a recognition of the role of agencies beyond government to influence decision making. The focus on local knowledge and on three policy-network levels (the policy maker, those who put the policy into practice and those impacted by the policy) is relatively unique in such studies (Cf. Wynne, 1992). Furthermore, the work has integrated the considerations of Tenbensel (2005) who considered the differences between links within the network associations, and stressed the different "modes of governance" that are used to apply pressure within the network.

From a discourse analysis viewpoint the decisions made at the Darlington meeting in 1990 represent the formation of a discourse coalition (Bulkeley, 2000) between the previously adversarial discourse coalitions of the academic sphere (who argued there was a forest effect) and forest management (who, argued that the "forest effect" was not proven; see Chapter 3). From a discourse analysis point of view The *Forest and Water Guidelines*, which represent this agreement, effectively shut down academic critique of the FC's approach leaving the FC in a position where they could self-govern their policy. This is not to say that the FC did not up date their work in line with new research (Cf. inclusion of nitrate impacts (Neal *et al.*, 1992) and NEGTAP (2001)), but more that the academic sphere no longer strongly critiqued the approach taken, and that there is no evidence of articles suggesting a wider "forest effect" (reviewed in section 4.4.) influencing the *Forest and Water Guidelines*. This coalition forming is seen in Bulkeley (2000) in the "*alliance of convenience*" formed between the "greenhouse action coalition" and the "resource-based discourse coalition" over the "no regrets" storyline that focussed on cost-effective approaches to climate change, to the benefit of both parties. However, whereas in the work of Bulkeley (2000) the coalition of convenience is seen as ultimately empowering, encouraging movement forward for both parties, the work here argues the inverse. By forming a coalition with the Forestry Commission over the "forest effect" the academic community effectively handed over the reigns of scientific critique to the FC, and left them to regulate themselves. They did this and focussed on the sulphate-scavenging "forest effect" that had been agreed at the expense of any others (see 3.2.5d; Miller, 1980; Neal *et al.*, 1992; Larssen and Holme, 2006).

In this chapter it was shown that the creation of the *Forest and Water Guidelines* effectively prevented both local FC management and the SRPB/SEPA from acting on local beliefs surrounding a wider "forest effect". For local forest management this is an example of the exertion of a hierarchical network pressure (Tenbensel, 2005). For local FC the *Forest and Water Guidelines* represent guidance to which they must adhere; actions can be taken beyond the guidelines, but resource will be focused on the areas indicated by the *Forest and Water Guidelines*. For SEPA, it was not hierarchical pressure, but professional network pressures (Tenbensel, 2005) that prevented the integration of local knowledge surrounding the wider "forest effect". Again, the formation of strong coalitions between organisations is shown to be a potential factor that can restrict openness to external information.

In terms of factors which encourage the transfer of knowledge, this chapter identified that the most effective process by which views surrounding the wider "forest effect" discourse were put into practice was by a) the development of relationships between the GFT and FC at policy implementer level and b) by lobbying public bodies external to the "forest effect" network so as to encourage them to apply their hierarchical pressures to the Forestry Commission regional advisory panel. The first example (a) study suggests that openness to voluntary professional network/community bonds (Tenbensel, 2005) outside of the core policy community[17] (Bulkeley, 2000) is positive in terms of knowledge transfer, and encourages access to Better Available Knowledge. The second example shows that disenfranchised actors within the policy network can affect action by forming coalitions with otherwise neutral parties within the wider policy community, and that the hierarchical powers these agencies wield are enough to

[17] Policy community: taken here to mean those with legal powers to influence policy, in contrast to the policy network which includes any interested party; see Bulkeley (2000).

disrupt existing agreed coalitions so as to change forest management in the favour of the wider "forest effect".

It is important to note that this chapter is discussed in terms of the factors which impact knowledge-transfer around the concepts of a wider "forest effect" without making any judgements as to whether this knowledge transfer will help or hinder the management of the "forest effect". It is true that the social learning approach views factors that encourage knowledge transfer as likely to encourage more informed decision making (Ison *et al.*, 2007; Blackthorn *et al.*, 2007). However, the extent to which the inclusion of outside knowledge is truly effective as a means of mitigating the "forest effect" remains unclear because the "forest effect" itself remains unclear (Chapter 4 :). If the Forestry Commission's mechanism-down view is correct, adapting forest management in the Bladnoch or the Fleet will offer little mitigation of the problems of acidification; however, if the wider "forest effect" is occurring then the *Forest and Water Guidelines* are failing to identify the areas where forestry produces the greatest risk. The remaining chapters draw on quantitative data sources, both collected specifically for this thesis and extant within the region, to create a database of best available data (Chapter 6). These data are analysed to map and discuss stakeholder viewpoints around the "forest effect" (Chapter 7) and which provide scientific insight into the nature of the "forest effect" (Chapters 8, Chapter 9). By combining the stakeholder views from the previous chapters with the quantitative-data-based insights from the chapters that follow Chapter 10 evaluates the extent to which the knowledge-transfer relationships identified in this chapter affect the transfer of Best Available Knowledge to forestry policy and practice.

5.6 The direction for further research

As discussed in section 2.3, this thesis has aimed to follow a stakeholder-based approach. The discussion presented in Chapters 3-5 provides a detailed research context to this, drawn, not only from an analysis of the literature, but also from participant observation and semi-structured interviews with local stakeholders and policy makers. It has been demonstrated that the Forestry Commission policy maker's perception of the "forest effect" is based strongly on the interpretation of the science of the scavenging "forest effect" mechanism. This mechanism-down view has been shown not match the perceptions of local stakeholders, although the extent to which this is the case rests on the Critical Loads model, currently untested at a regional scale in Galloway. Furthermore, it has been demonstrated that the relationships between stakeholders are key factors that both encourage and restrict the transfer of knowledge regarding the "forest effect". To address the thesis' aim, of determining the factors that influence the extent to which forestry policy and practice incorporate Best Available Knowledge, the following chapters of this thesis target the research questions below:

How can Best Available Data be collated and combined to contribute positively to understandings around the "forest effect"? **(Chapter 6 :)**

To what extent does inter-stakeholder discussion of mapped "forest effects" influence the inclusion of different knowledges in forestry policy and practice? **(Chapter 7 :)**

Is there scientific evidence for wider "forest effect" beyond that represented in the Forest and Water Guidelines? **(Chapter 8 :)**

Is there scientific evidence for a "forest effect" on long-term trends of water chemistry and the recovery from acidification? **(Chapter 9 :)**

Chapter 6 : Quantitative Data and Methods

6.1 Introduction

Chapter 4 : highlighted two closely linked problems: i) it is unclear as to whether the areas at risk of acidification highlighted by the *Forest and Water Guidelines* match with the understanding of the environment held by local stakeholders; and ii) there is a difference in belief between local stakeholders and policy makers as to whether there is any evidence for a "forest effect" beyond the areas covered by the guidelines. Furthermore, it was demonstrated that, although long-term records of water chemistry and fisheries are available within the region, and forest information can be successfully estimated from satellite imagery, these datasets have rarely been successfully combined to resolve questions about the "forest effect" or the way that it is represented in policy.

To resolve these issues three research questions (below) were developed to be tackled in the chapters that follow:-

- Chapter 7 :: To what extent does inter-stakeholder discussion of mapped forest effects influence the inclusion and exclusions of different knowledges in forestry policy and practice?

- Chapter 8 :: Is there statistical evidence for wider "forest effect" beyond that represented in the *Forest and Water Guidelines*?

- Chapter 9 :: Is there statistical evidence for a "forest effect" on long-term trends of water chemistry and the recovery from acidification?

It is the aim of this chapter to determine how best available data can be collated and combined to contribute to understandings around the "forest effect". To address this, two data products are developed: a) ***stakeholder-based maps*** that represent the areas of risk highlighted by Forestry Commission and SEPA policy, and local fisheries data from the GFT; and b) a ***catchment-based database*** that can be probed statistically to answer questions about the "forest effect" and its long-term impacts on recovery.

The section that follows identifies: a) the data products required to answer these questions (6.1.1); b) the sources of these data; and c) the processing steps required to produce outputs for the chapters that follow.

6.1.1 Data requirements for the two data products

6.1.1a Stakeholder-based mapping

The aim of the stakeholder-based mapping approach is to draw on regional data to stimulate discussion between all stakeholders and evaluate the extent to which this discussion will lead to management actions that will change the impact of forestry policy and practice on acidification. For this approach, data requirements are governed by the individual datasets used by the three main stakeholders: the FC, the GFT and SEPA. The creation of these layers requires the collection and GIS processing of datasets in line with creation of the catchment-based database below; the detail of the stakeholder-based mapping is discussed in section 6.6.2.

6.1.1b Catchment-based database

A statistical analysis of the "forest effect" requires forestry variables to be related to water chemistry variables. In addition, complicating catchment factors such as geology, sulphate deposition, rainfall and altitude need to be taken into consideration. Catchments need to be determined for the upslope contributing areas of each water quality sample and the proportion of each catchment-variable (e.g. forestry, sulphate deposition) within these catchments needs to be quantified. By doing this, a database of linked water quality-catchment data can be produced for statistical analysis. By including water quality data linked to individual years of forest data as well as long-term records of forest change, questions regarding both the wider "forest effect" (Chapter 8 :) and the "forest effect" on recovery (Chapter 9 :) can be answered.

Table 6-1 summarises the datasets required for both products. They come in two types: water quality datasets (point source indicators of impacts) and catchment-scale datasets (spatially distributed potential causal factors). The following sections present these data sources and the approaches applied to generate them; water quality datasets are discussed in section 6.2 (water chemistry), 6.3 (SEPA WFD classification) and 6.4 (fisheries) whilst catchment variables are discussed in section 6.5. The final products are introduced in section 6.6.

Table 6-1 Tasks and datasets

	(W)ater Quality/ (C)atchment variable	Stakeholder-Based Mapping: SEPA WFD characterisation	*Forest and Water Guidelines*: Critical Loads exceedance	*Forest and Water Guidelines*: 300m rule	Fisheries viewpoint	Statistical Analysis: Is there a wider "forest effect"?	Is there a "forest effect" on recovery?
Long-term water chemistry data*	W						✓
Water chemistry data*	W		✓			✓	
SEPA characterisation	W	✓					
Fisheries data	W				✓	✓	
Forest structural data	C			✓		✓	✓
Catchment geology	C					✓	✓
Catchment sulphate deposition	C		✓			✓	✓
Catchment altitude	C			✓		✓	✓
Catchment rainfall	C		✓			✓	✓

*includes pH, alkalinity, DOC, anion and cation data (see section 6.2)

Note: In the following sections when a new variable is introduced, it is highlighted in its initial instance with the following ***font***. This is the variable name by which it is referred to within the catchment-based database; it is flagged as an indication that it may be referred using an abbreviation from that point on. A list of the meaning of these variables and their shorthand names is given in Table 6-9 at the end of this chapter.

6.2 Water Chemistry Datasets

Table 6-2 Available water chemistry datasets

Year	Dataset	Laboratory*	Source	Base/High	Date(s)
1996	**Puhr_1996**	**S(D)**	**Puhr and Donoghue (2000)**	**High flow**	**12th March**
2005	UoD_2005	UoD	This Thesis	High flow	16th March
2005	SEPA_2005	S(EK)	This Thesis (Quality Control)	High flow	16th March
2006	**UoD_2006**	**UoD**	**This Thesis**	**High flow**	**8th March**
2006	FC_2006	FC	This Thesis (Quality Control)	High flow	8th March
Ongoing	SEPA_LT	S(EK)/S(D)	SRPB/SEPA Monitoring	Base Flow	Long-term 1956-ongoing

*Laboratory codes: -
S(EK) = SEPA Laboratories (East Kilbride, used from 17th May 1999)
S(D) = SEPA Laboratories (Dumfries)
UoD = University of Durham Geography Department Laboratories
FC = FC Laboratories, Alice Holt, Surrey.

Six water chemistry datasets are included in this study (Table 6-2). The following sections introduce these datasets and describe the processing steps by which they were prepared for integration into the two data products. The site locations for these datasets are listed in Appendix B, the data themselves are stored in Appendix I

6.2.1 Single-date high-flow surveys

During high-flow conditions, the greater volume of precipitation and run off means that greater amounts of pollution are deposited via wet deposition, scavenged sulphate on vegetation is transferred to the hydrosphere, and due to bulk inputs waters spend less time in the soils where buffering is possible. Furthermore, whilst acid inputs are increased in this way, base cation buffering in waters is diluted by the increased fluid volume. As a result pulses of high pH and aluminium have been noted by many authors during high flow events (Burns *et al.*, 1984; Welsh and Burns, 1987) often linked to fish deaths (GFT, 1989). It is for this reason that the *Forest and Water Guidelines* recommend that samples for the Critical Loads model are taken under high-flow conditions.

As long-term monitoring within the region (section 4.4.1d) does not target high-flow conditions it has been necessary for authors such as Puhr *et al.* (2000) to specifically target these events. This project follows a similar methodology and coordinated field sampling during storm events in 2005 and 2006.

6.2.1a Puhr 1996

In March 1996 Chris Puhr of the University of Durham coordinated the collection of a high-flow regional sample of 95 headwater catchments with the specific aim of identifying the extent of the "forest effect" in Galloway (published as Puhr *et al.* 2000 see 4.4.1c). Puhr's data were available for this project and analysed at SRPB/SEPA labs in Dumfries (see Table 6-2) prior to the movement of the laboratory to East Kilbride. The concerns raised about the sulphate data after the laboratory move (see section 6.2.1e) are not therefore a concern for Puhr's data.

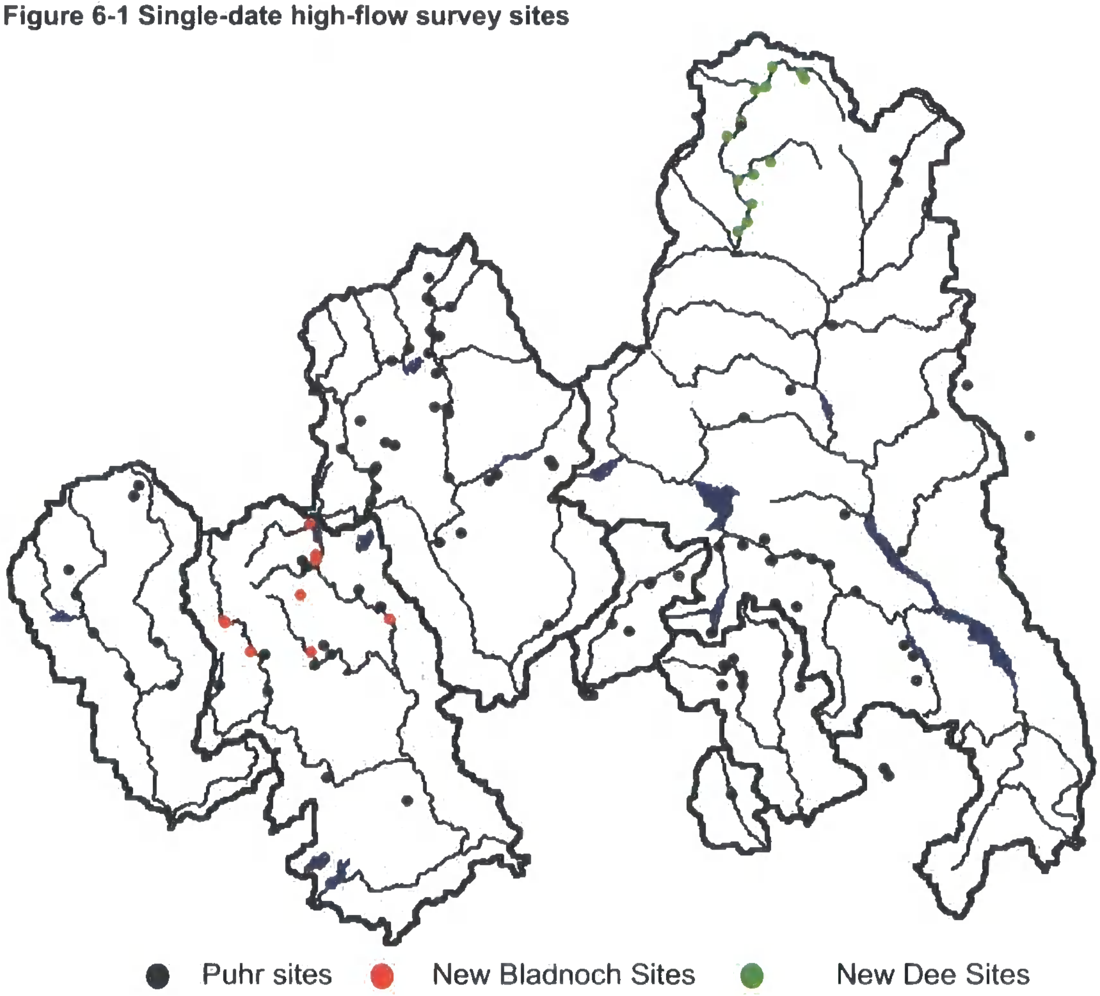
6.2.1b Single-Date Regional Surveys design

The data collected for this project in 2005/6 followed the methodology set down by Puhr (1997) as the two projects had broadly the same aims. It was also recognised that following the same methodology and targeting the same catchments as those monitored in 1996 would allow for long-term comparisons between the two datasets, almost 10 years apart.

To minimise factors other than forestry that have the potential to impact water quality, Puhr (1997) designed his methodology ensuring and selected 95 sites that fulfilled the following criteria:

i) Catchments were as similar to one another as possible in terms of physical catchment characteristics except catchment afforestation.
ii) Catchments of mixed geology were excluded (using a <95% cut-off).
iii) Sites represent the full range of catchment afforestation (0-100%) encountered in the Galloway Region.
iv) Sites were checked with the GFT to ensure that they provided suitable environments for juvenile salmonids.

Figure 6-1 Single-date high-flow survey sites



In consultation with SEPA, the Forestry Commission and the Galloway Fisheries Trust, it was agreed that a re-sampling would take place in Winter/Spring 2005. Puhr's sites would be resampled and an additional 14 sites in the High Dee and 8 sites in the Bladnoch would be added. These sites were added at the request of SEPA and the

Forestry Commission as a means of getting additional information on areas planned for restocking (in the Bladnoch) and areas of older forest due for felling (in the Dee). In total 117 sites were involved in the survey (Figure 4-1).

6.2.1c Field Survey

Two full surveys, 16th March 2005 and 8th March 2006, were performed with the assistance of SEPA, the Forestry Commission and Galloway Fisheries Trust. Six survey teams were deployed each equipped with 1 litre sample bottles and pre-written labels. Any sites planned for double (or triple) sampling were clearly marked. Water-proof field maps specific to each team were provided indicating the location of each site with a field description as well as coordinates. Both surveys were successfully completed within 1 day following the storm event. The hydrographs of each event show that flow in the rivers was at least double low flow conditions in each of the three storm events (Appendix C).

6.2.1d Laboratory Method (Durham)

Table 6-3 Lab methodology Durham/SEPA

Variable	Durham (Geography Department Laboratories) Methodology	SEPA (East Kilbride) Methodology (as of 2007)
pH	Taken with YSI 556 multi-parameter probe designed for low ionic strength waters.	By Titration using Radiometer Titralab TIM 900
Chloride (Cl)	Use DIONEX DX500 machine EG50 eluent generator LC25 chromatography oven to maintain temperature. 2mm AS17 & AG17 columns. Samples from refrigerated ASAP from survey.	AQUA 800 Colorimetric methods
Nitrate ($NO_3(N)$)		
Sulphate (SO_4)		
Sodium (Na)		Varian Vista Pro Inductively Coupled Plasma-Optical Emission Spectrometer (ICP-OES)
Potassium (K)		
Magnesium (Mg)		
Calcium (Ca)		
Alkalinity (Alk)	By Titration	By Titration using Radiometer Titralab TIM 900
Dissolved Organic Carbon (DOC)	Follow Standard Methods	Filter through .45μm membrane Oxidise organic carbon sample Detect and quantify CO_2 produced using Non-Dispersive Infrared Detector Present in terms

Samples from both surveys were analysed in the Geography Department Science Laboratories at the University of Durham. Samples were stored in ice packed cool boxes and delivered to the laboratory on the day of the survey. At the laboratory samples were stored in a +4°C refrigerator and analysed as quickly as possible to minimise any chemical alteration. The Durham laboratory methodology is summarised in Table 6-3.

6.2.1e Inter-lab verification and the Sulphate Issue

Figure 6-2 2005 SEPA/University of Durham Inter-Laboratory Comparison

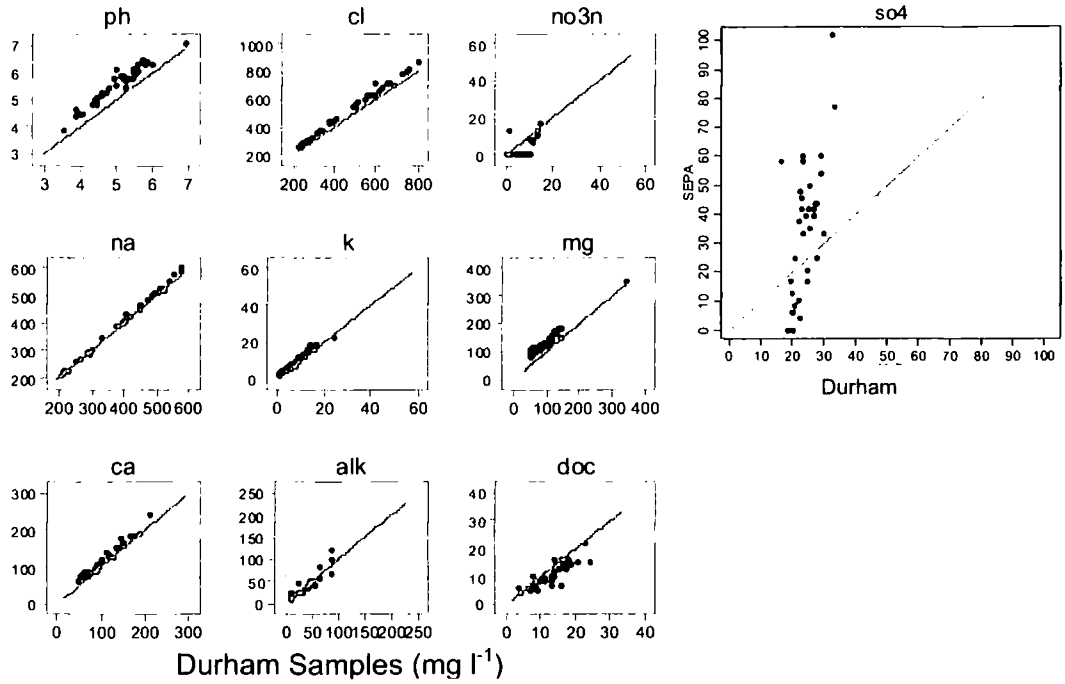
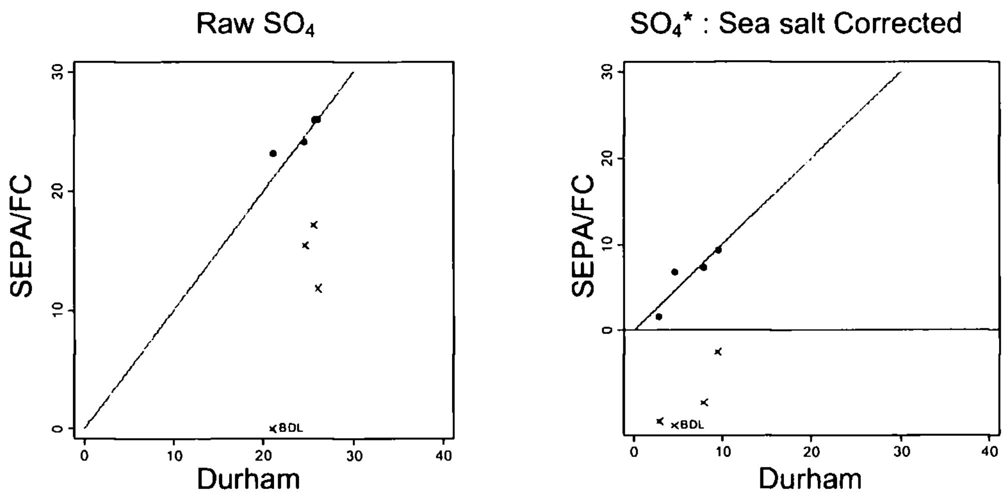


Figure 6-3 Sulphate comparison analysis: Durham/SEPA/FC labs



× SEPA East Kilbride (Blah) • Forestry Commission Alice Holt (DIONEX)

Both plotted against UoD Lab sulphate result using DIONEX ion chromatography. Values in mg/l.

As, for discussions of policy, reliable data in which all stakeholders believe is of paramount importance, it was arranged for the 2005 survey that SEPA would take a double sample of 22 of the sites (all sites in the Bladnoch, and a control sample from Skyre Burn) to analyse in their own accredited labs at East Kilbride. The results from this inter-lab comparison are presented in Figure 6-2.

Figure 6-2 shows that whilst the majority of anions and cations, pH and DOC, were well correlated, sulphate and nitrate values were very different between the two labs. To resolve the issue a third lab (that of the forestry commission at Alice Holt) was included in a re-analysis of four samples.

The reanalysis validated the Durham results showing strong collinearity between Forestry Commission laboratories and those at Durham for all determinants. Figure 6-3 shows the comparisons between the three labs for sulphate; it is clear that sulphate is consistently under-predicted by the SEPA laboratory, and that this has particularly significant consequences when the sulphate data are corrected for sea salt deposition within the Critical Loads model (see 3.2.6a(iv)). The reason for the difference was agreed to result from a difference in lab methodology: Durham and Forestry Commission laboratories both use a Dionex ion chromatography approach designed to measure at low ionic strengths; the colorimetric methods selected for use by the SEPA laboratory were not designed for such low ionic levels, as the majority of SEPA's work focuses on pollution events from less 'natural' pollution sources such as chemical or effluent spills. After discussions between the Forestry Commission Hydrologist and SEPA laboratories in East Kilbride, SEPA laboratories have modified their practice, changing their approach: a recent cross-validation (2008) showed that both their nitrate and sulphate levels now correlate well with the Dionex measured values of both Forestry Commission and Durham laboratories.

The importance of factors such as these in the scientific process is significant in terms of the any claim of privilege by scientific knowledges. It is for reasons such as these that Latour and Woolgar (1979) argue context should not be written out of the discussion of science practice. From a more pragmatic perspective, problems such as these do stress the fact that it is vitally important to ensure that the limits to knowledge available with science are taken into consideration during the decision making process. It is important that policy makers and scientists alike ensure that when they refer to data they are aware of the uncertainties associated and that the error of scientific input is recognised in the predictions output, and that rather than being politically neutral and objective these reflect pragmatic decisions made data during data collection, input and analysis.

6.2.2 SEPA/SRPB long-term water chemistry data

SEPA control a large amount of data including both long-term operational monitoring data collected by the SRPB/SEPA[18] and the high-resolution long-term data recorded at the five study sites of the Loch Dee project. Of these data the operational monitoring data (discussed in 4.4.1 and 5.2.3) had been collected since the mid-1950s but has seen little use in the academic literature (notable exceptions being Helliwell *et al.*, 2001 and Tervet *et al.*,1995) whilst the Loch Dee data had been used in a variety of academic articles (e.g. Burns *et al.*, 1984; Nisbet *et al.*, 1995) with the most recent being Langan and Hirst (2004).

The operational monitoring data consists of four annual samples usually split evenly between summer and winter months, whilst the Loch Dee data include weekly/bi-weekly samples collected since 1980. Neither dataset was specifically targeted at high-flow conditions recommended for targeting by the *Forest and Water Guidelines*, as they were not collected for this purpose[19]. This does however mean that they are less likely to represent the worst-case scenarios present during storm events (Burns et al, 1984) or acid flushes. Nonetheless, they are the best available long-term dataset and provide an impressive regional and temporal distribution with 68 sites, the majority of which have over 10 years of data (Figure 6-4). Access to these data was granted by SEPA and all data for the 68 sites was downloaded.

Water chemistry data for each of these sites were provided as Excel spreadsheets from the SEPA database.

As with any long-term regional-scale record, it is important to take into consideration a number of issues when interpreting long-term trends in the data. These include:

- data acquisition
- variations in the methodology of data acquisition
- variations in the motivation behind the sampling
- variations in temporal resolution of the data between sites
- laboratory issues
- changes in laboratory
- changes in analytical practice
- changes in data recording practice

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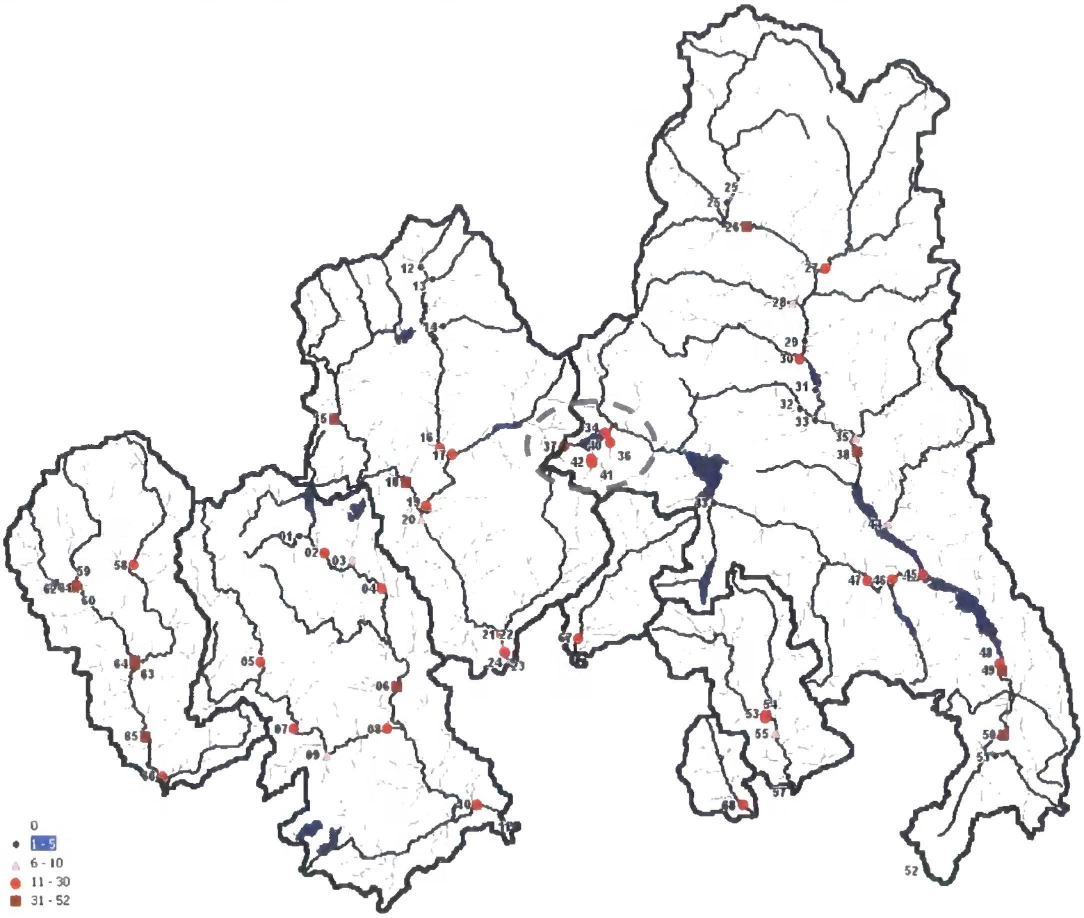
[18] The Solway River Purification Board (SRPB) were integrated into the Scottish Environmental Protection Agency (SEPA) in 1996; their monitoring remained unchanged (SEPA-G).

[19] In this thesis these "non-high-flow" samples are referred to as median-flow as they are later processed to the annual median value of the samples. To my knowledge the samples were not targeted at any specific flow, but captured during the conditions present on the day sampled. "Median flow" is therefore short-hand for "median of four non-high-flow samples" and not intended to indicate that the samples were collected when river flow was at its median stage.

6.2.2a SRPB/SEPA data acquisition considerations

Figure 6-4 SEPA long-term data: regional and temporal distribution (Legend symbols shows number of years of data; Labels show site numbers.)



Of the problems surrounding data acquisition, the methodology of data acquisition is unlikely to be a source of major error; even though the samples will have been collected by a variety of individuals for a variety of purposes, standard methodologies exist for field sampling and there is no reason to believe that these are not followed in practice. It is, however, worth noting that the operational monitoring and Loch Dee datasets were collected for very different reasons, with the operational monitoring data accrued for the purposes of reporting at a national scale and the data from the Loch Dee Project designed to study long-term trends in acidification. This is reflected mostly in their temporal resolution, but also in the extent to which they have been referred to in the published literature.

6.2.2b SRPB/SEPA laboratory considerations

Analysis for the SEPA/SRPB dataset has taken place at one of two SEPA laboratories: prior to May 17th 1999 all samples were performed in Dumfries; after this time laboratory analysis was moved to East Kilbride. Although inter-lab calibration tests were applied at the time of the move, recent work has identified that changes in lab practice have implications for both the long-term sulphate record (see 6.2.1e) and alkalinity data (Langan and Hirst, 2004)

Langan and Hirst (2004), working on the Loch Dee data identified the issues with the SEPA sulphate data, discussed in section 6.2.1e, which they also put down to "*methods of analysis*", arguing that sulphate levels were "*lower than expected*". In addition they reveal problems early on in the data record. As a solution to these problems they excluded sulphate data from 1981-1983 and post 1998 from analysis; this thesis also excludes these data. They identify similar problems with alkalinity data stating that "*in compiling the data it became obvious that the undertaking, determination and reporting of alkalinity have varied through the record*" and decide that "*whilst recognising the importance of alkalinity as a parameter in indicating acidification status the authors decided to exclude the data because of the uncertainty of determining a trend due to environmental change as opposed to one introduced through determination and analysis*" (Langan and Hirst, 2004). For this reason alkalinity data are also excluded from this project.

It should also be noted that as a result of the exclusion of sulphate data from the more recent long-term record it is impossible to calculate derived variables such as Charge Balance ANC or Critical Loads exceedance (see 6.2.3b).

6.2.3 Water chemistry: Key Parameters

Figure 6-4 shows the distribution of sites monitored by SEPA/SRPB through time. The exact chemical parameters monitored vary with time and site.

Table 6-4 Variables available within datasets

	Directly Measured										Derived		
Dataset	pH	DOC	Cl	SO_4	$NO_3(N)$	Alkalinity	Ca	Mg	Na	K	xSO_4	ANC_{CB}	CLoadX
Puhr 1996	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Durham 2005/2006	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
SEPA long-term	✓	a	✓	b			✓	✓	✓	✓	b	b	b

a: Available for 2005
b: Available 1983-1998

Table 6-4 lists the available datasets and the water chemistry parameters present within each one. The following section describes each variable in terms of its relevance to acidification studies and explains any problems regarding the availability of the data.

6.2.3a Directly measured parameters

1. **pH.** pH is a direct measure of the hydrogen ion content of the water, and its acid/base status. It is recognised that fish survival is reduced at low pH with pH 5.5 often quoted as a critical threshold (Harriman and Langan, 1992) for salmon. As a result, pH is the variable for which the most data are available.
2. **Cl.** Chloride is one of the key variables monitored by the AWMN. It provides an indication of the influence of sea salt deposition on the chemical record as well as providing an acid anion to the hydrological system. Chloride is an important element within the Critical Loads model as the means for correcting for sea salt inputs (see section 3.2.6a(iv)).
3. **SO_4**. Sulphate present in fresh water is assumed to be atmospheric in origin. A large proportion of this is from pollutant sources whilst the remainder is natural originating from deposition of marine salts. The AWMN uses sea salt corrected sulphate (xSO_4; derived variable 4) in its long-term monitoring studies; both marine and anthropogenic sulphate are scavenged by forestry, and both contribute to the acidification of rivers so a comparison between xSO_4 and SO_4 is of interest.
4. **NO_3(N)**. Nitrate is another source of acid anions; whereas anthropogenic sulphate is known to be on the decrease, nitrogen is considered to be increasing (AWMN, 2004; Shilland et al., 2007). Nitrogen can come from both anthropogenic (e.g. power stations, agriculture and transport) and natural (e.g. igneous rocks or plant and animal debris) sources. As nitrogen is needed for plant growth, it is thought that this nitrogen uptake by plants will to some extent counteract the acidification impact of additional pollutant inputs (Harriman *et al.*, 2003).
5. **Alkalinity**. Alkalinity is strongly related to pH and is "usually taken as an indication of the concentration of carbonate, bicarbonate and hydroxide" (Chapman, 1992). In practice it is usually the result of a titration with a strong base to a set pH, and is therefore a measure of all buffering ions present in the solution. For this reason it can often be found referred to in the literature as Acid Neutralising Capacity (ANC), although in this project it should be kept distinct from the derived ANC variable (ANC_{CB}) defined below. Locations with low Alkalinity are very susceptible to small changes in pH and thus more prone to acidification. As illustrated in section 6.2.2 the alkalinity data within the SEPA record is seen as unreliable and so is excluded from this project, although alkalinity is available for the high-flow Durham data.

6. **DOC**. Dissolved Organic Carbon (DOC) is a variable noted by the AWMN as being on the increase in upland rivers. DOC is an indication of the amount of weak organic acids (such as fulvic or humic acids) present in the watercourse. It is a variable that has only recently become a focus of scientific research and as a result is one of the variables for which least data are available for the Galloway region.
7. **Ca.** and **Mg.** Both Calcium and Magnesium are key base cations readily dissolved from sedimentary rocks but not from rocks which are harder to weather (e.g. granites and other igneous rocks). Increased acid ion inputs can often lead to an increased in base cation leaching in response; these cations play a significant role in buffering against acidification. The AWMN uses the derived variable Ca+Mg as a measure of base cation buffering available in a water body; however, it was decided to treat these two variables separately within this project to determine if either was particularly impacted by the "forest effect".
8. **Na.** Sodium is highly soluble and found in plant and animal matter; in coastal regions such as Galloway it is often found in increased amounts as a result of sea salt from rainfall. It is a base cation and contributes to buffering capacity in the Critical Loads model.
9. **K.** Potassium is also a base cation, but plays only a minor role in buffering acid inputs because it is generally found in low concentrations in surface waters.

6.2.3b Derived Variables

1. **xSO_4**. Sea salt corrected Sulphate (**xSO_4** also referred to as SO_4^*) which uses knowledge of the water's chloride value and the proportion of sulphate found in saltwater to convert SO_4 to anthropogenic SO_4 values by removing the sea salt derived sulphate proportion (see 3.2.6a).
2. **ANC_{CB}**. Charge Balance ANC is commonly found in the literature, as it is easily calculable with commonly available Anion and Cation values. It is ΣBase Cations – Σacid Anions, or Na + Ca + Mg + K – NO_3 – SO_4 – Cl. It is criticised as not being as sensitive as ANC_{AB} used by Evans *et al.* (2001), and will be particularly sensitive to errors associated with sea salts (Evans *et al.*, 2001). Nonetheless it is a summary variable that is calculable from the data available in this project. Alternative means of calculating ANC were explored including Evans *et al.* (2001) and Cantrell (1990) however lack of reliable alkalinity and aluminium data meant that only ANC_{CB} was used in this thesis.
3. **CLoadX.** Critical load exceedances are calculated as described in section 3.2.6a and Appendix A. A number of variations of the input parameters are applied to produce a variety of different Critical Loads exceedance scenarios for

the stakeholder-based mapping. The scenarios created are detailed in section 6.6.2b, and the current *Forest and Water Guidelines* scenario is selected from them and used as the variable "CLoadX" within the catchment-based database (6.6).

6.2.3b(i) A note on Aluminium

Aluminium, although recognised as an important variable in the impacts of acidification, particularly on ecology (Johnson *et al.*, 1981; Bull and Hall, 1986; Ormerod *et al.*, 1987; Ormerod *et al.*, 1989), was not collected within the project. The explanation for this was for a combination of pragmatic reasons of cost and time as the projects focus on the existing environmental management practice leading to a focus on the Forestry Commission's Critical Loads approach and the variables required for it.

6.2.4 Water Chemistry Data Processing

The methodological approach involved collating numerous Microsoft Excel spreadsheets into a single database within the statistical package Stata. The database was processed to a format in which each record was unique in terms of the survey it was taken from, the year it was collected and the site from which it was taken. For the three high-flow surveys each record represented a single high-flow sample from that site. For the SEPA long-term data, each record represented the median value at that site; sites with less than four samples were excluded. For the SEPA long-term data other summary statistics (mean, minimum and maximum) were also extracted; there were 14,392 SEPA long-term records in total. All chemical determinants were converted to micro-equivalents per litre (μeql^{-1}) these units represent the weight in grams of a substance that will produce or react with 1 mole of hydrogen ion or 1 mole of electrons; concentrations are therefore equivalent in terms of the ionic charge they contribute to an acid/base titration. They are calculated in relation to their molar mass and their ionic charge (see for Appendix E.1 the equations). All values recorded as Below the Detectable Limit (BDL) were replaced by DL/2 following the approach of Hornung and Reed (1990). More robust approaches that impute values such as those recommended by both Bacarrelli *et al.* (2005) and Helsel (2006) were considered too complex for the small number of BDL samples present within the dataset; this is, however, discussed in Appendix E.2.

All data were subjected to data screening to minimise the impacts of outliers; this is standard practice when dealing with water chemistry data, and in doing so the importance of following a robust methodology is paramount. As such the approaches taken by organisations such as CLRTAP (2006) and the AWMN (Davies *et al.*, 2005a) were followed, and outliers only removed if it was clear that they were outside the local distribution. Three methods were applied. Firstly, Cl:Na ratios of greater than 1.5 or less than 0.5 were excluded following the methodology of CLRTAP (2006); this led to the removal of 151 records. Secondly, the AWMN sites were used as an indication of data spread and all sites outside of its limits were considered for removal; only sites that were also far removed from local distributions were excluded; this led to the modification of at most 65 sites.

$$\text{Equation 6-1: Charge Balance \% (CB\%)} = \frac{\Sigma \text{ Base Cations} - \Sigma \text{ Acid Anions}}{\Sigma \text{ Base Cations} + \Sigma \text{ Acid Anions}} * 100$$

Figure 6-5 Water chemistry data processing methodology

Field Survey →	Long-term Monitoring	Loch Dee Project	1996 Field Survey	2005 Field Survey	2006 Field Survey
Laboratory	SEPA (D/EK)		SEPA (D)	UoD	UoD
Survey Name	SEPA_LT		Puhr_1996	UoD_2005	UoD_2006
Data Format	68 Spreadsheets (.xls)		1 .xls	1 .xls	1 .xls
Individual Spreadsheets	• 71 Excel Spreadcheets • Filter for key variables and order (VBA Macro):- pH, SO_4, NO_3(N), Cl, Na, K, Ca, Mg, Alkalinity and DOC • Additional Information:- Site name, easting, northing, sampling date. • Combine into one sheet.				
	EXCEL DATABASE				
Pre-Stata processing	• Give Unique ID by site Numbers1-117: Puhr & Durham Sites Numbers 201-268: SEPA_LT Sites • SEPA_LT ID overrules for the 3 sites that exist in both networks • Export site locations to GIS for pour-points • Move data to statistical software				→ GIS
	STATA DATABASE				
Data management	• Convert data from milligrams/litre → micro-equivalents/litre • Check for redundant/duplicate data • Ensure 1 record/day/site (replace with mean) • Remove SEPA_LT alkalinity data • Remove SEPA_LT SO_4 data outside the period 1983-1998				
Data Screening	• Na:Cl checks • Compare with AWMN data • Ion balance checks				
Calculate Derived variables	• xSO_4 • ANC_{CB} • ANC_{CA} • 4 x CLoad Scenarios				
Generating Site Summary variables	• Puhr and Durham data have only one record • Summary Statistics for SEPA_LT data Annual (if ≥ 4 records) Median, Mean, Maximum and Minimum				
Water Chemistry Database	• Database ready to join with Fish / Catchment Data				

The final step in the screening process applied charge balance checks (following Evans *et al.*, 2003; CLRTAP, 2006); these approaches assume the electro-neutrality of water and that the majority of ionic charge is contributed by strong acid anions (SO_4 NO_3 Cl) and base cations (Na Mg Ca K); see Equation 6-1. CLRTAP (2006) recommends the exclusion of all values where the charge balance difference is over ±10%. This was impractical for the Galloway samples as the median balance for all sites was +8.73 $\mu eq l^{-1}$ (cations greater than anions) and following the ±10% criteria would therefore have required the removal of over 2000 records. As the underestimation of the anion content of waters was expected to come from the role played by organic acids (DOC is excluded from Equation 6-1), it was decided to retain charge balance errors within the dataset. A more detailed analysis of these issues can be found in Appendix E.

After following these steps, the three derived variables, listed in 6.2.3b were created, with four Critical Loads exceedance scenarios produced as explained in section 6.6.2d. Figure 6-5 summarises this methodological approach.

6.3 SEPA WFD characterisation

6.3.1 SEPA WFD characterisation

6.3.1a WFD characterisation

In its role as lead authority on the WFD, it was necessary for SEPA to have performed an initial characterisation of water bodies in terms of their risk of failing the Water Framework Directive by 2004. This was achieved and rivers were classified into the first four categories shown in Table 6-5.

Table 6-5 SEPA classification classes

1A	"likely to fail the good status targets of the WFD
1B	"will probably fail the WFD"
2A	"will probably pass the WFD"
2B	"likely to meet the good status targets of the WFD".

In addition to information on the risk of failure, these data included the "pressure" that was seen to be contributing to this risk and the "sector" seen to be responsible for the issue. Acidification is represented in the SEPA coding system as a site with a "diffuse pollution" pressure which is attributed to both "electricity, gas and water supply" and "forestry, logging and related activities" or "agriculture and forestry". The acidification classification drew on data pre-existing at the time of the characterisation exercise; it focussed on invertebrate and diatom data as they were seen to be "the most vulnerable indicator species"; fish data were not used in the classification (7.2.1c).

6.3.1b Data availability and processing

SEPA supplied its WFD water bodies layers as an ArcGIS shapefile. Data processing using an Excel macro filtered through the sites to identify those where acidification was identified as a consideration (as described above). A final GIS layer was produced which classified sites in terms of the risk of acidification contributing to a failure of the WFD using the classes in Table 6-5 with an additional class "N/A" for rivers where acidification was not identified as a pressure. This layer was then ready for stakeholder based mapping (see section 6.6.2).

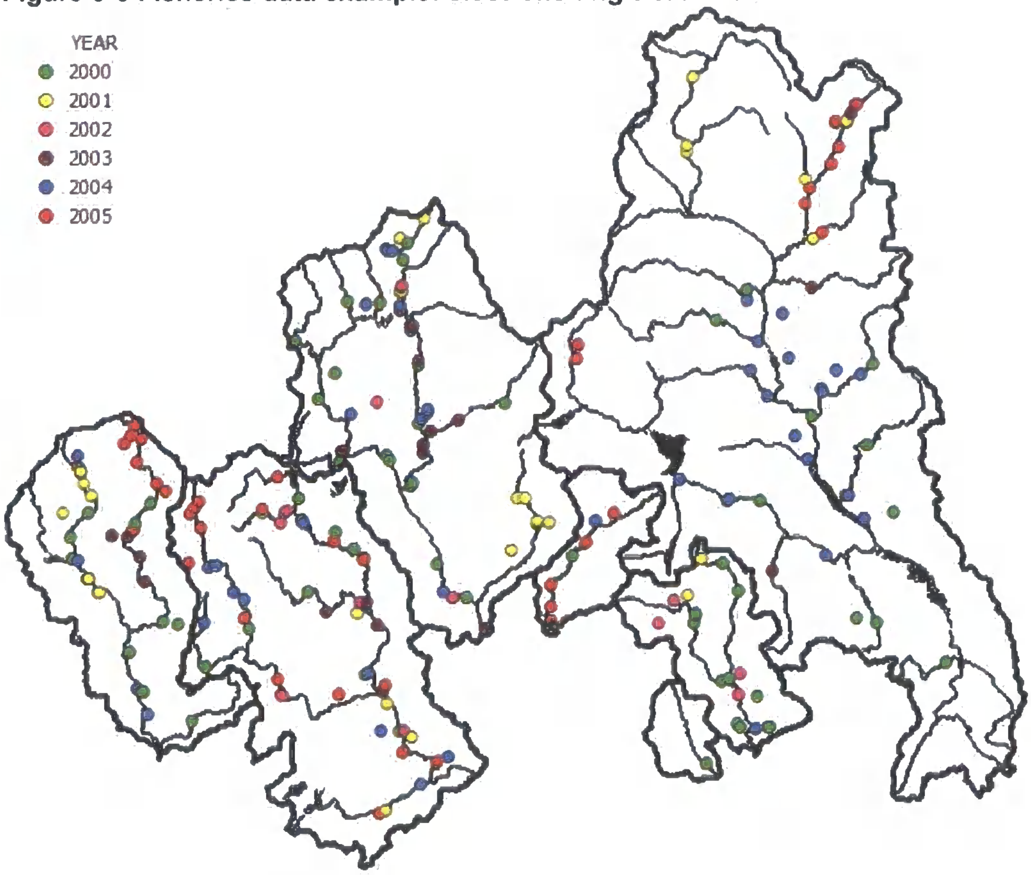
6.4 Long-term Fisheries Datasets 1989-Now

Fisheries data were also processed for inclusion within the thesis. Unfortunately, after joining there were very few sites in which forestry, fisheries and water chemistry were available, except for the data from 1995 which have already been analysed to show a "forest effect" on fisheries in Puhr (1997). As a result the analysis has been excluded from the main body of the text: it is presented below for interest. A further extension to this project that extracts catchment forestry for each catchment for which there is fish data would be very useful, allowing a contemporary analysis of "forest effect" on fisheries to be determined.

6.4.1 Available Data

As described in section 5.2.2c the GFT have been collecting electrofishing data in Galloway since 1989. The data cover the region and focus on many small burns and tributaries most sensitive to acidification and any "forest effect"; Figure 6-6 illustrates how widely spread the samples are by showing the distribution for sites from 2000-2005. All available electrofishing data were made available to this project. Their electrofishing methodology is laid out in its first annual report (GFT, 1989), and the GFT (pers comm.) confirm that there has been little change to it since that time.

Figure 6-6 Fisheries data example: electrofishing sites 2000-2005



The electrofishing data available (Table 6-6) include fish counts rather than fish mass. The data include the numbers of salmon and trout in both the fry (0+ years) and parr (1+ years) age classes. Data from 1997-2006 was provided in Excel format output from the Scottish Fisheries Coordination Centre (SFCC) database. These data, are as data are entered, automatically checked to assure that factors such as the geographical positional accuracy of the sample were considered. Data before 1997 were available in the GFT annual reports; this information had not been entered in a digital format; it was transcribed within this project to produce a second GFT dataset from 1989-1996.

Table 6-6 Available fisheries datasets

Source	Dataset	Format	s0	s1	t0	t1
GFT	1989-1996	Reports	✓	✓	✓	✓
GFT	1997-2006	Excel Spreadsheet	✓	✓	✓	✓
s0 = salmon fry aged 0-1 years (0+) s1 = salmon fry aged 1-2 years (1+) t0 = trout fry aged 0-1 years (0+) t1 = trout fry aged 1-2 years (1+)						

6.4.2 Processing the 1989-1996 Data

6.4.2a Data entry checking

Both the 1989-1996 Fish Data and the 1989-1996 Plot Location Data were checked as best possible to remove any errors from data entry; any errors found were corrected to match with the values in the reports.

6.4.2b Finding missing locations

Plot locations were not recorded in the reports for fifteen sites. These sites were located where possible using their description and the later GFT survey data or Chris Puhr's field data from 1995. Where this was not possible, sites were dropped unless the description was sufficiently clear to allow the site to be located on an OS map with sufficient accuracy (e.g. "Outflow Loch Trool"). Seven sites were dropped in this fashion; of these none were long-term sites and were either outside the study area or targeted for a specific purpose (such as monitoring the impacts of adding a pipeline).

In one instance the same Location ID is used for two separate sites, at two separate XY coordinates. These sites were separated into two separate sites.

6.4.2c Processing the 1997-2005 data

Data from the SFCC database was assumed to have gone through the rigorous requirements to be entered into the database and so was not in need of further checking. Data from 2000-2005 was converted directly from the SFCC output to a GIS shapefile for the stakeholder-based mapping (section 6.6.2).

6.4.3 Joining 1989-1996 and 1997-2006 datasets

The 1989-1996 and 1997-2006 fish datasets were joined using the methodology outlined in section 1.2.7a below.

6.4.3a Linking data based on location

The following sub-section describes the method by which sites from different surveys are checked to determine whether or not they may be treated for the purposes of this study as the same location.

Grid references are used to convert data from the surveys of interest into GIS shapefiles. Once in a GIS format the "NEAR" algorithm in ArcGIS was run to return the distance between the points in the two surveys.

Sites over 200m apart were treated as different sites. All sites below 200m apart were examined individually within the GIS. By comparison of the locations against the OS base map a sites were deemed to be the same only if they were clearly on the same tributary with no other tributaries between them. The site description was used as a guide when there were two potential rivers within reach, and any locations where it was unclear whether sites were the same sites were treated as separate.

As a result of this analysis an index file was created that linked the sites from the two surveys to one another. This index file was used as a joining table by which a combined database which included the information of both datasets could be created.

6.4.3b Multiple samples at a site in a year

In some, very rare, instances the GFT sampled the same site multiple times in a year. In such cases the maximum fish number recorded at the site was taken as the representative fish stock for that site-year. This means that the final database contains one record per site per year. There are 911 records over X possible fish sites for the years 1989 – 2006.

6.4.4 Confounding issues and considerations

6.4.4a Fish Stocking

Since 1989 the GFT and other Galloway fisheries interests have undertaken fish stocking (both salmon and trout) in some areas where fish populations were under threat or lost. As a result these populations may have unrealistically large populations for their chemical/catchment conditions. Information on whether a site is "stocked" or not is available within both GFT datasets. As a result stocking year was included for each site. To avoid this complicating factor information on fish stocking needs to be included in any analysis, and stocked sites removed from the analysis for the two years after stocking. Ribbens (pers comm.) suggests that after two years any fish survival will not have been influenced by the stocking and that the site can again be seen to having a representative fish population to be included in the analysis

6.4.4b Fish Access

At the other end of the spectrum, unnaturally low fish numbers for a specific chemical/catchment condition may be found if there is a physical barrier that prevents fish movement. To minimise the impacts on the results the Galloway Fisheries Trust looked over all sites identified as fishless and determined the sites which fish were unable to reach. These sites were removed from the analysis. The highly detailed GFT

Reports were also cross-referenced to ensure that issues of fish access prior to 1996 were also taken into consideration.

6.4.4c Zippin Considerations

All GFT data use the Zippin (Zippin, 1958) methodology to provide statistics designed to compensate for the impact of repeatedly fishing a river stretch, and to take into consideration the area of river surveyed. The Zippin approach converts fish catches from a sequence of runs to a closed population value per unit area. For long-term studies the GFT follow an approach of three run surveying, but for rapid regional assessment it is "not uncommon for a single run to be conducted" GFT(1989). In these conditions it is impossible to provide an error term. In this project the Zippin value itself is used without reference to an error term, and 3 run sites and 1 run sites are seen as comparable. Any errors that result from this will not impact the presence/absence of a species, but could provide minor influences on the regression analysis.

6.4.4d Young fish are not indicators of adult populations

Care must be taken when interpreting the presence/absence of young fish for adult stock assessment as mortalities subsequent to spawning may mean that an absent fry/parr population is not necessarily an indication of a lack of adult migration. The data are instead designed to be an indication of salmon and trout spawning, and the presence of fish should be seen as a sign that that section of river is at least healthy enough to support fish in the more vulnerable stages of their lifecycle.

6.4.4e Derived variables and inclusion within the database

Figure 6-7 summarises the methodological approach taken above. On completion the four fish age classes were included within the catchment-based database as the variables "***s0***", salmon fry 0-1 years in age; "***s1***", salmon parr 1-2 years in age; "*t0*", trout fry 0-1 years in age and "***t1***", trout parr 1-2 years in age. Two derived variables were also generated for analysis; these were "***max_fish***", the maximum number of fish found in any age/species class found at the site (i.e. Max[s0 s1 t0 t1]) and "***total_fish***", the total fish in any of the four age/species classes (s0+s1+t0+t1).

Figure 6-7 Fish data processing methodology

Stage		
Field Survey	GFT Electrofishing Methodology	
Data Source	1989-1996 GFT Reports	SFCC Database
Format	Written reports	Excel Spreadsheet .xls → GIS
Transposition/ Checking	• Transcribe to Excel Spreadsheet • Data entry checking • Identify missing locations • Fish stocking data transposed also • XY coordinates used to create GIS shapefile	• Data entry fullfilled SFCC protocol; assumed accurate. • Fish stocking data part of database • XY coordinates used to create GIS shapefile
	ARC GIS	
Spatial Join	• Join by spatil proximity • NEAR function in ARC • All sites > 200m apart deemed different • All sites < 200m apart checked in reference to site name • Uncertain sites excluded • Join table created and two datasets linked by joint ID	
	STATA DATABASE	
Data management	• Multiple surveys – same year: replaced with maximum fish. • Fish stocking: removed data from sites if stocked with fish within last 2 years (following GFT pers. Comm..) • Fish Access: verified "no fish" sites with GFT not due to access	
Fisheries Database	• Database ready to join with Water Chemistry / Catchment Data	

6.5 Catchment-Scale Datasets

6.5.1 Raw Data

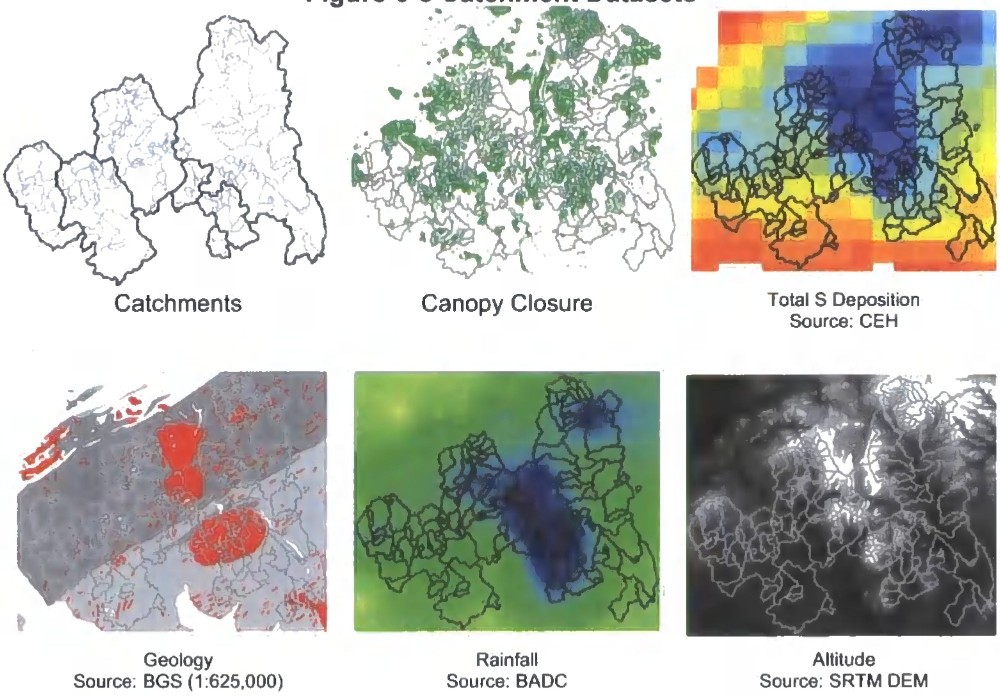
6.5.1a Rationale

The water quality datasets discussed in the two previous sections are indicators of acid impact. They are point data-sources, samples of either water chemistry or ecological health measured at a specific known XY location. For both of the data products described in it is important to be able to relate these impact indicators to factors (including forestry and sulphate deposition) that may have contributed to the extent of this impact. To do this it is necessary a) to know the catchment contributing area of each location for which point data are available and b) to be able to quantify the potential causal factors within this catchment area; sections 6.5.2 and 6.5.3 address these two issues respectively.

6.5.1b Data requirements and rationale

The key catchment datasets (Figure 6-8) were matched to the data products in Table 6-1, the scientific rationale for their selection is described below; more information on their acquirement and processing is discussed in the following sections (6.5.2-6.5.6).

Figure 6-8 Catchment Datasets



6.5.1b(i) Forest Structural Data.

As argued by Puhr (1997) and discussed in section 4.4.1e the detailed parameterisation of not only forest cover but *forest structure* within a catchment is vital to any study of the "forest effect". The methodology of Puhr and Donoghue (2000) is extended to long-term data within this project (Dunford and Donoghue, 2007; Appendix B) to generate five years of catchment-scale canopy closure information from 1989 – 2005. This is discussed in section 6.5.3

6.5.1b(ii) Catchment Total Sulphur Deposition.

Total Sulphur deposition drives the forest scavenging effect represented in the *Forest and Water Guidelines*. It is a key variable in the Critical Loads model and plays a significant role in acidification at a national and international scale (CLRTAP, 2001; AWMN, 2001).

6.5.1b(iii) Catchment Geology (and Soils).

Many studies (e.g. Hornung *et al.*, 1990; Langan and Wilson, 1992) demonstrated that geology and soils play an especially important role in determining vulnerability to freshwater acidification. In Galloway, Puhr *et al.* (2000) found that stratifying sites by the three main catchment geologies improved regression relationships. This study does not include soils data. There are four reasons for this: i) the sensitivity approach adopted the *Forest and Water Guidelines* is based on a classification by geology; ii) the sensitivity of soils is to a large part determined by the primary weathering material; iii) Puhr *et al.* (2000) demonstrated that geological differences were sufficient to separate sites in terms of acid sensitivity; iv) errors in terms of soils will stand out as outliers in distributions stratified by sensitivity and can be identified from this (e.g. Carsphairn in the upper Dee, in section 8.5.1b). The processing of geology data are found in section 6.5.5.

6.5.1b(iv) Catchment Rainfall.

Rainfall is a key variable in the Critical Loads model, used as a proxy for runoff. In addition, regional rainfall is a key driver in the hydrological cycle; the amount of available rain governs runoff, provides an indicator to the amount of wet and occult deposited pollution for a given sulphate deposition. Furthermore, regions with heavier rainfall are more likely to be subjected to worst-case high-flow conditions (see 1.2.1b) more regularly. The generation of a regional rainfall data layer is described in section 6.5.6.

6.5.1b(v) Catchment Altitude.

The 300m rule and the fact that occult deposition increases with altitude (Fowler *et al.*, 1989) mean that catchment altitude is a key factor; how to represent catchment altitude as a single value is however more complex. This is discussed in section 6.5.7.

The following sections address the method for catchment generation and then describe the means by which each of the catchment datasets is extracted from a geographically distributed data layer to a catchment-based summary statistic that could be joined with water quality data for that catchment. Section 6.5.2 provides an overview of the processing method by which these datasets were prepared within this project.

Figure 6-9 Catchment dataset extraction methodology

Dataset	OS Landform Panorama 50m DEM	Optical satellite imagery	BGS 1:625,000	CEH sulphate deposition	BADC Data
	ARC GIS				
Processing	• DEM Flow Direction Map • Fill sinks • Import chemistry site pour points • Generate catchments	• SWIR and tree height • Find model • Invert model • Maps of tree height • Apply to multiple years (5 images)	• Convert to raster	• Worst case scenario • Extrapolate to raster	• Filter Data • Convert records to GIS (Excel) • Model for missing years • Extrapolate to raster
Validation	• Validate catchments against OS raster	• Validate model against ground data • Correct for image deficiencies	• External dataset: no validation		• Comparison with raw data
Product	• Catchments • Altitude raster	• Forest Height Maps • 1989, 1995, 2001, 2003, 2005	• Geology raster • Igneous • Silurian • Ordovician	• Sulphate deposition raster • 1995/2004	• Average Rainfall Raster • 1980-2000
	STATA DATABASE				
Catchment Extraction	• Catchment altitude • Catchment Area	• Canopy closed forestry % • Small trees %	• Catchment Geology %s	• Catchment Sulphate	• Catchment Rainfall

6.5.2 Catchment Generation

6.5.2a Rationale

To be able to relate the influence of spatially distributed factors such as forestry, rainfall and pollutant deposition to water quality variables collected at specific locations knowledge is needed regarding the geographical catchment area that flows into that point and of the contribution that each spatially distributed factor makes to that catchment. To do this a catchment GIS layer was generated that could be applied as a 'cookie cutter' to the areal datasets. Significant bodies of work exist which draw on the use of digital elevation models (DEM) as a source of elevation data from which automated catchment units can be calculated and for which the potential errors are well documented (USGS, 1997; Walker and Willgoose, 1999; Holmes *et al.*, 2000; Wechsler, 2007). In light of many potential sources of error in catchment generation, the significant differences between representing the environment in a GIS and the complexity of the environment in reality, it is recognised that the final catchments will never be more than a best approximation of the catchment area. The section below details the methodology used by this project, and the steps required to assure that the automated method matches reality.

6.5.2b OS Land-Form Panorama Data (50m)

An OS 50m DEM was available for the purposes of this project. The product is a digital representation of graphical contours from the UK ordnance survey Land Ranger map series. These contours in vector format would be at 10m intervals, with spot heights recorded to the nearest metre; the raster product available for this project contained grid cells of $50m^2$ (Ordnance Survey, 2004). Other DEMs, such as the 10m OS Landform Profile (Ordnance Survey, 2005) and the 90m SRTM DEM (http://srtm.usgs.gov), were also considered. The 50m DEM was preferred as it provided a reasonable balance between processing speed and accuracy and had been previously demonstrated to provide sufficient accuracy in the work of Puhr (1997).

6.5.2c DEM processing

Standard DEM catchment generation methodologies were followed using ArcGIS Hydrology tools. Burning rivers into a DEM to ensure flow along known pathways is a common practice in DEM manipulation; however it was found to offer no significant benefit and is not included in the methodology below.

6.5.2c(i) Step 1: Flow direction.

A map of flow direction is generated from the digital DEM. The D8 method is used for this. Each DEM pixel is compared with the eight pixels surrounding it, and the maximum slope is identified. Flow direction is allocated as an eight point compass direction.

6.5.2c(ii) Step 2: Fill sinks.

For the purposes of automated stream delineation it is necessary to fill any artificial sinks in the terrain, such as those over lakes, otherwise flow will never continue beyond a lake to the sea. The Fill sink methodology identified these areas, and artificially adjusts the DEM upwards to allow water to encourage flow.

6.5.2c(iii) Step 3: Import pour point layer.

Identify the locations of sites for which catchment generation is required. In this project both SEPA/SRPB chemistry sites and University of Durham chemistry sites were used as pour points (the locations for which catchments are delineated). Fisheries sites were not used; this would be a very useful further extension to the project allowing the comparison of fish catches with forest data for areas where chemistry data were unavailable.

6.5.2c(iv) Step 4: Generate Catchments

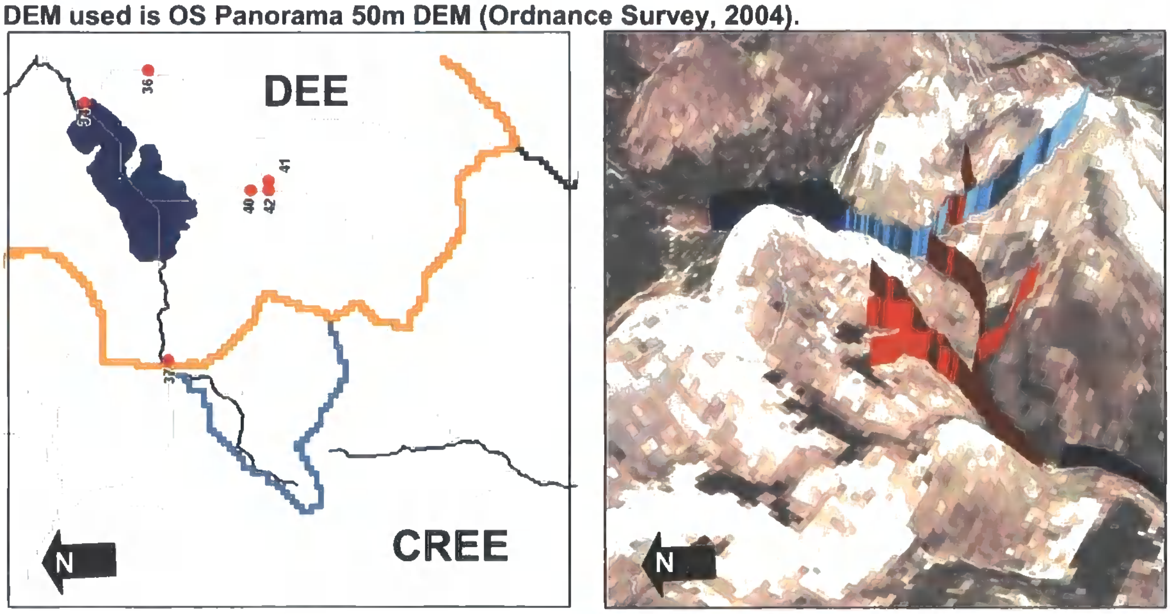
GIS uses the selected pour points and works backwards up the flow direction raster to identify all cells which contribute flow to that pour-point. The result is a raster layer numbered by pour-point catchment.

6.5.2c(v) Step 5: Manually Verify Catchments:

Sites were checked for two types of error and corrected the OS 1:10,000 raster as geographical "truth"; in any circumstances where generated catchments did not match those expected from an interpretation of the OS Raster, catchments were manually corrected to match. There were two types of error identified:-

The first errors included those where the pour-point location did not match that of the DEM river, due to inaccuracies of site location, or DEM river generation; these errors were corrected for by moving the pour-point to a cell on the DEM river. Each catchment adjusted in this way was checked against the OS raster to assure accuracy.

Figure 6-10 DEM error: an example of the Dargall Lane showing the importance of DEM checking by comparing automatically generated and manually corrected catchments. DEM used is OS Panorama 50m DEM (Ordnance Survey, 2004).



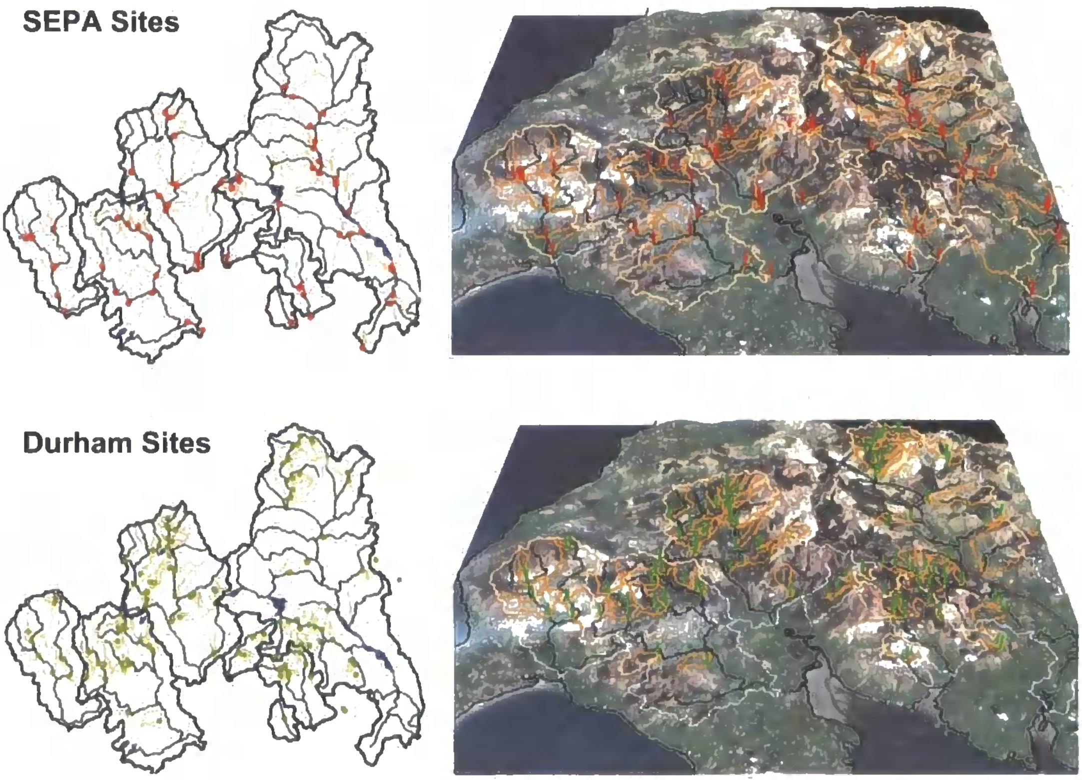
Comparing Catchments
DEM generated
Corrected to real
Pour Point 37

Comparing Rivers
DEM generated
Corrected to real

The second error type occurred when the DEM generated river and catchment did not itself match geographical reality as represented by the OS raster. This error was less common, but quite significant when found. Figure 6-10 below shows an example of this for the Loch Dee project and AWMN site the Dargall Lane; due to the steep topology the DEM allocated river (in red) flows into the Cree Catchment. In reality the river follows the blue line and flows into Loch Dee. Any of the second type of errors were manually corrected to match the OS raster.

The completion of this step resulted in a final GIS catchment layers for both SEPA and Durham surveys (Figure 6-11).

Figure 6-11 Final catchments generated using Ordnance Survey 50m DEM and (Ordnance Survey, 2004) and pour points from both SEPA long-term monitoring sites and University of Durham high-flow survey sites (2D / 3D).



6.5.2d Method of extraction

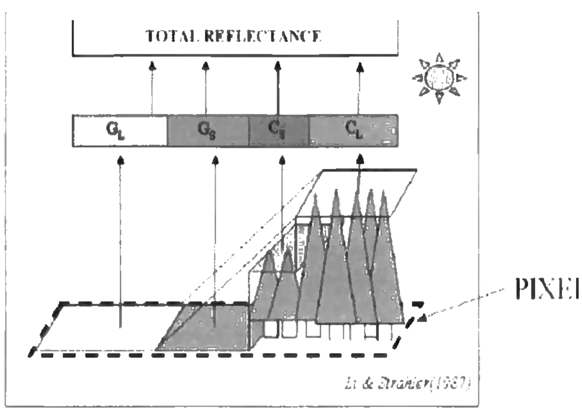
With catchment layers complete, a merged file that is the union of SEPA and Durham catchments is used as a "cookie cutter" and applied to each individual catchment dataset to extract summary statistics. Each catchment dataset was resized to a maximum of 10m^2 pixels to ensure that any mixed pixel problems were likely to be very small in relationship to the overall size of the catchment. The "zonal statistics" function in Arc GIS was then used to extract data to a statistics file by catchment; the summary statistics chosen vary in relation to the dataset extracted. The following sections (sections 6.5.3-6.5.8) discuss the catchment datasets in terms of the processing steps required to prepare them for data extraction, the summary statistics selected and the variables produced for inclusion within the catchment-based database as a result.

6.5.3 Catchment Forestry Datasets

6.5.3a Background

Significant research (Puhr and Donoghue, 2000; Donoghue *et al.*, 2004; Donoghue and Watt, 2006; Donoghue *et al.*, 2007; Dunford and Donoghue, 2007) has demonstrated that the height of UK upland forestry plantations can be successfully estimated using optical satellite imagery. This work is based on the relationship between reflectance in optical imagery and forest height identified by Li and Strahler (1985). Li and Strahler's theory is based on the fact that forest canopy is reflectance is significantly different to that of ground vegetation particularly in the short-wave infrared (SWIR) part of the electromagnetic spectrum. As a forest establishes the proportions of more reflective ground vegetation are replaced with increasing proportions of lit canopy and shaded canopy and ground (Figure 6-12). Once canopy closure is attained, forest height no longer influences the proportion of ground vegetation visible to the sensor and the limit of the predictive power is reached. For managed forests districts in the UK this limit has been shown to be at 13m in height (Puhr and Donoghue, 2000).

Figure 6-12 Li and Strahler (1985) contributions of forestry to pixel reflectance in optical imagery.



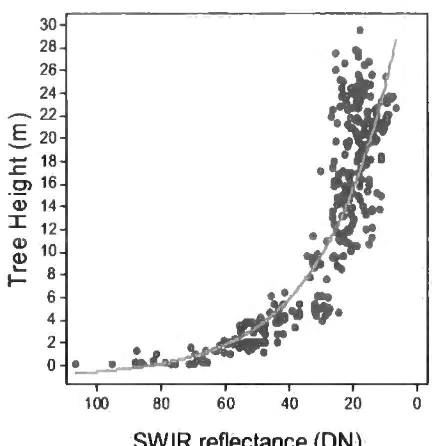
- Lit Ground cover (G_L)
- Lit Canopy (C_L)
- Shaded Ground cover (G_S)
- Shaded Canopy (C_S)

Forest growth to canopy closure can be monitored by inverting this model and using SWIR reflectance as an indicator of forest height. It is necessary to determine a relationship between field-measured forest plot height data and the satellite image SWIR reflectance for that plot. Following this methodology Puhr and Donoghue (2000) derived strongly significant relationships between for Galloway (R^2 = 0.94 P<0.01). Further work extended the methodology showing that the relationship was robust across different optical sensors (SPOT, Donoghue *et al.*, 2004, IKONOS Watt and Donoghue, 2007) and forests (Galloway Forest, Puhr and Donoghue, 2000, Donoghue et al., 2004; Kielder Forest, Watt and Donoghue 2006) again producing highly significant results (R^2 0.818, P<0.01, RMSE 0.984m). Once determined such regression equations can be inverted to produce regional maps of tree height based on the image (Puhr and Donoghue, 2000; Watt and Donoghue 2006).

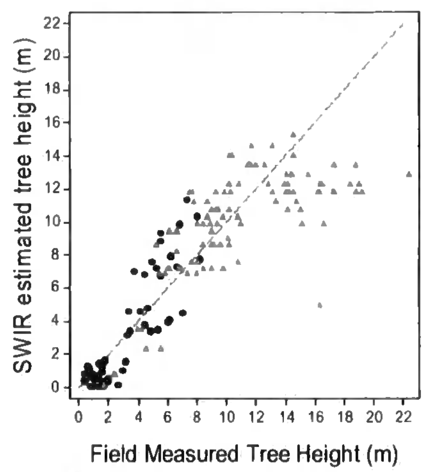
6.5.3b Long-term Methodology

For these methodologies to work in practice, a field dataset contemporary to the optical satellite image is required. This field dataset must cover the range of forest age classes to canopy closure so as to be able to calibrate the SWIR height model. For studies such as this where field data are not necessarily available for all images an alternative approach must be taken. Dunford and Donoghue (2007, Appendix B) describes in detail the methodology by which a single image:field dataset pair may be used to classify a series of radiometrically corrected images for the purposes of generation of a time series of forest height maps. Using this methodology 360 height measurements were extracted from a LiDAR data layer from 2003 and used to generate a model with the SWIR band of a spot image from the same year (R^2 = 0.88, RMSE 1.53m Figure 6-13a).

Figure 6-13 Tree height estimation from optical imagery
a) relationship b) evaluation (from Dunford *et al.*, 2007)



a) Scatter of SPOT SWIR reflectance from 2003 with LiDAR height (also 2003) for 360 plots. Grey Line is fitted logarithmic regression Tree Height = 10^(1.60– 0.02* SWIR). R2 = 0.88, RMSE 1.53m



b) SWIR estimated tree height vs. 155 independent measured tree height plots (black 1995; grey 2001)

Equation 6-2 SWIR-estimated tree height = 10^(([$SWIR_5$] * -0.01905) + 1.6005)

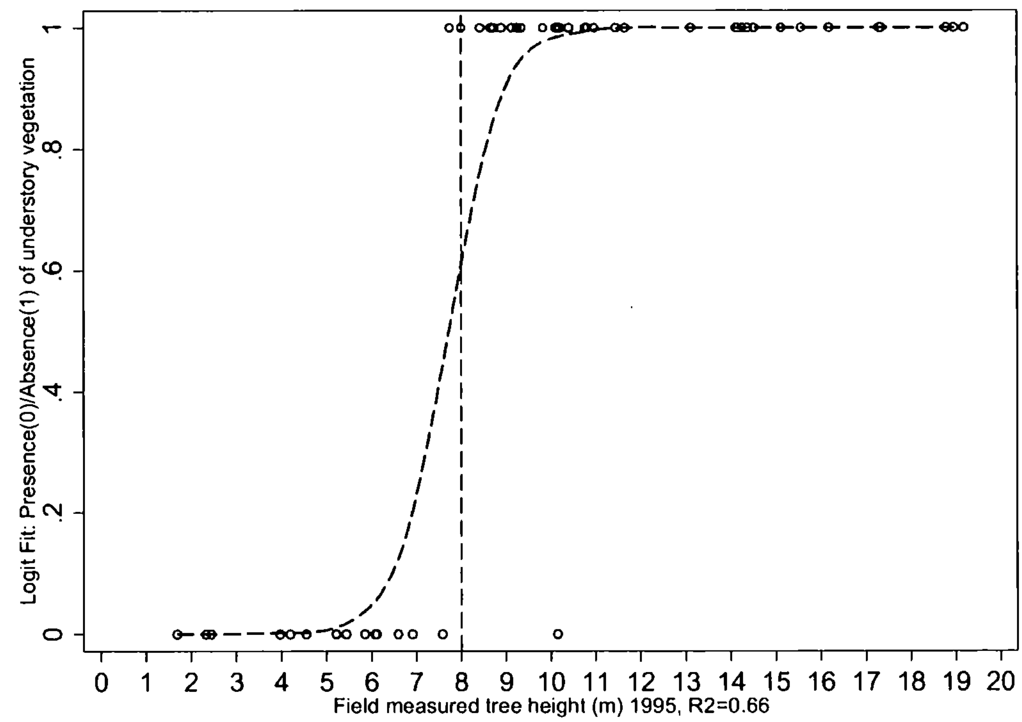
Six optical images were available for analysis in this study. These images were radiometrically corrected to one another under the ForestSAFE project (ForestSAFE, 2006) and cover the period 1989-2005 and with a temporal resolution of approximately 5 years (Table 6-7). Two images from 2003 were combined to minimise issues of image extent (from the SPOT image) and cloud cover (in the Landsat Image). The model in Figure 6-13a was inverted (Equation 6-2) and applied to the SWIR band of each of the six images to produce maps of estimated tree height.

Table 6-7 Available satellite imagery

Date	Image	Notes
11/07/1989	Landsat TM	None
21/06/1995	Landsat TM	None
01/05/2001	Landsat ETM	Some minor cloud issues
09/01/2003	Landsat TM	Severe cloud in western scene
17/04/2003	SPOT 5	East Galloway only
24/04//2005	SPOT 5	None

These maps were validated by comparing estimated height values with field survey data from 1995 (from Puhr, 1997) and 2001 (from Donoghue et al, 2004). The validation is shown in Figure 6-13b and show the model to have a mean error of ±1.43m up to 13m in height at which point canopy closure restricts predictive ability (Puhr and Donoghue, 2000).

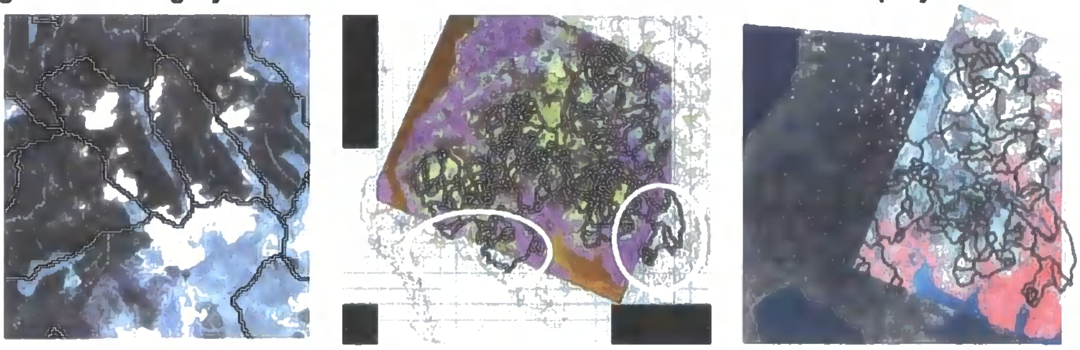
Figure 6-14 Logistic regression of presence/absence of understorey vegetation against tree height from Puhr and Donoghue (2000). 8m, the tree height at which point understorey vegetation is no longer present is taken as canopy closure



6.5.3c Correcting for imagery constraints

As with any automated methodology it is important to manually verify that errors within the images are corrected for. Each image was checked individually to correct for image impacts that would lead to the misclassification of forestry cover. Appendix F details the corrections made, however they can be summarised into the three types illustrated in Figure 6-15a-c. The first issue is the presence of cloud cover obscuring underlying land use data, which was corrected for with reference to data from other years. The second was corrected in a similar way but resulted from variations in the image extent. The third issue arose from a combination of the other two problems and was resolved by combining two optical images of the east (with excessive cloud) and west (with a small image extent) of the region. The resulting image minimised both problems.

Figure 6-15 Imagery constraints identified and corrected for within this project.



a) Cloud Cover 2001   b) Imagery Extent All Years   c) Combining Images 2003

6.5.3d Forest height products

As a result of the above methodology five forest variables were created for the catchment-based database. In addition the maps of forest height themselves provide context for other analyses.

6.5.3d(i) Forest Height Maps (SWAIH)

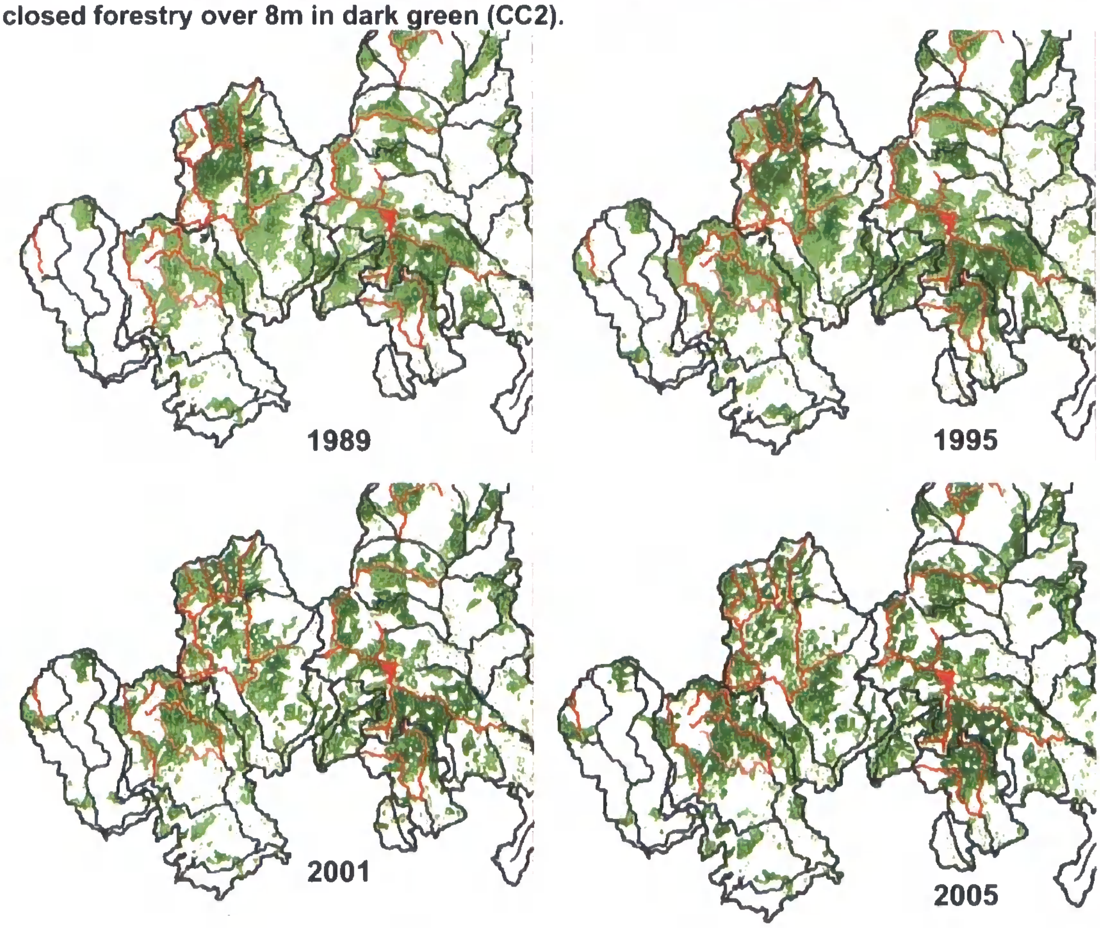
The raw forest height maps showing predicted tree height. In recognition of the failure of predictive power beyond 13m all pixels above this value were classified as 13m in height. On extraction by catchment (6.5.2d) as an average catchment height this value is equivalent to Puhr (1997)'s "structurally weighted afforestation index of height" or SWAI-H; analysis (8.3.2) showed this to correlate so significantly (r=0.988) with canopy-closed forestry (CC2 below) that it was excluded from all analyses.

6.5.3d(ii) Maps by Canopy Class (CC1, CC2)

As the SWAI-H index's "average catchment forest height" is a relatively abstract construct, proportional variables representing the catchment forestry was divided into forestry before and after canopy closure. To identify canopy closure a tree height of 8 meters was used following Puhr and Donoghue (2000) who identify 8 metres as the tree height at which understorey vegetation cease to be present (Figure 6-14, R^2 0.66). In addition, a lower limit of 2m is used, as trees below this height are hard to distinguish from background vegetation on medium resolution (20-30m) imagery.

Following this tree height maps were reclassified into binary layers containing the two canopy closure classes; CC1, trees between 2-8m and CC2, trees over 8m in height. On extraction by catchment the proportion of the catchment under each canopy closure class was available for inclusion within the catchment-based database. In the process the layers were renamed: young trees (SWIR-estimated-height between 2 and 8m) were named "canopy class one" which is referred to in this thesis by the shorthand ***"CC1"*** and canopy-closed forestry (SWIR-estimated height >8m) was named "canopy class two" and is referred to in this thesis by the shorthand ***"CC2"***. Figure 6-16 shows how CC1 and CC2 change through time for four of the five images.

Figure 6-16 Forest height change maps generated using the methodology of Dunford *et al.* (2007). Images show young trees between 2-8m in light green (CC1) and canopy closed forestry over 8m in dark green (CC2).



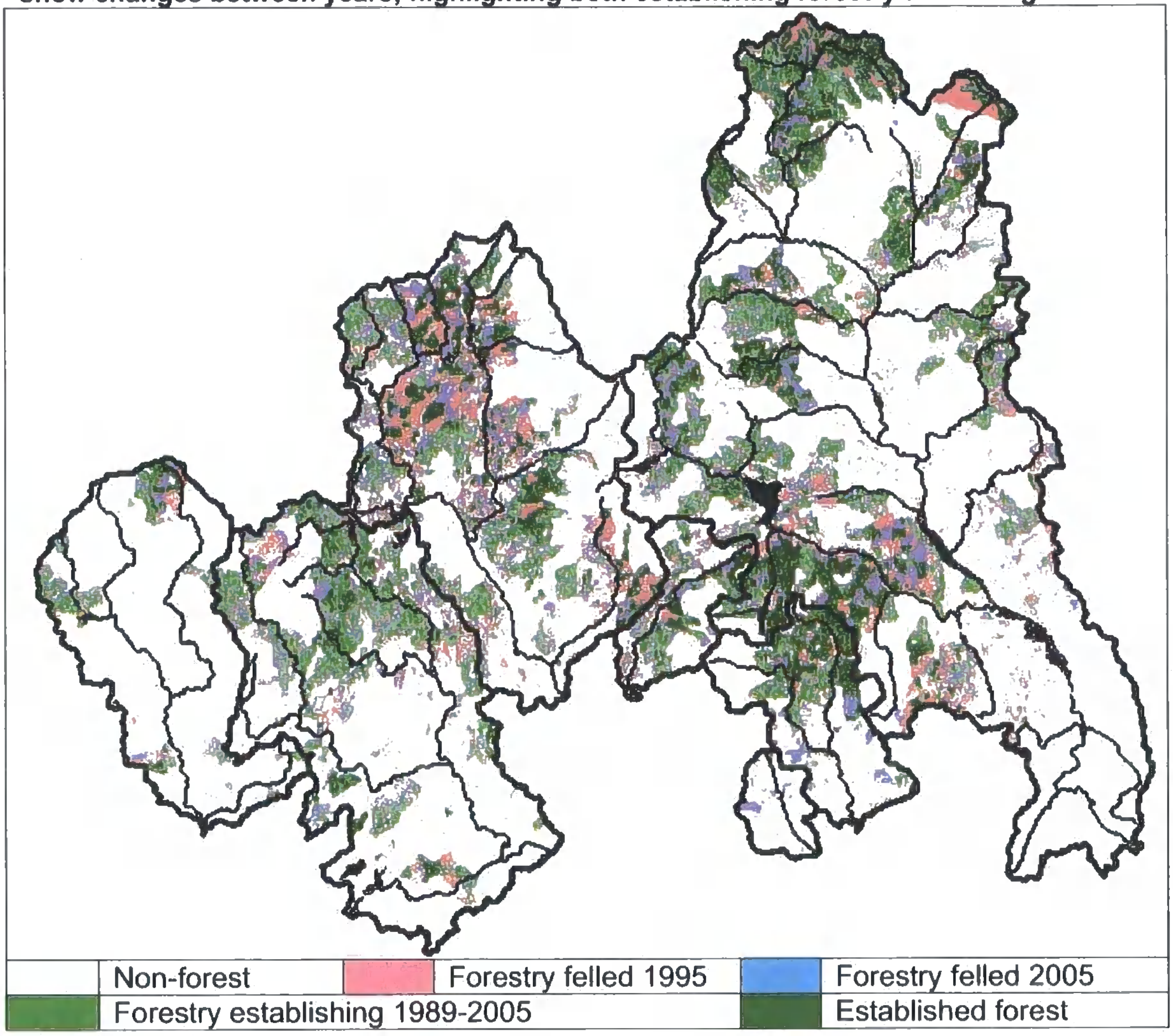
6.5.3d(iii) Canopy classes over 300m (CC1_o300, CC2_o300)

To include the 300m rule (4.2.2e) in the forestry dataset the proportion of each of the canopy classes CC1 and CC2 that was found above the 300m contour was also created as two binary layers. These were extracted in a similar way to CC1 and CC2 and are referred to in this thesis as "***CC1_o300***"and "***CC2_o300***" respectively.

6.5.3d(iv) Map of Change

By combining CC2 data from multiple years it is possible produce a map of forest change highlighting felled areas as well as areas of forest growth, long-term established forestry (Figure 6-17). This is particularly useful as a qualitative reference tool when looking at regional distributions of data in Chapter 7 and long-term trends in forestry in Chapter 9 :.

Figure 6-17 Forest change maps generated by combining maps of 1989, 1995 and 2005 to show changes between years; highlighting both establishing forestry and fellings.



6.5.4 Sulphate Deposition

Table 6-8 Total Sulphur deposition datasets

Year	Modelled/Measured	Scale
1970	FRAME Model Output	$5km^2$
1980	FRAME Model Output	$5km^2$
1995-7	CEH combined model method	$5km^2$
2001-3	CEH combined model method	$1km^2$

Four sulphate deposition datasets (Table 6-8) were available from the Centre of Ecology and Hydrology (CEH). The datasets for 1970 and 1980 are generated using the FRAME model (Dore *et al.*, 2007); they are not included in the analysis within this project but are shown in Figure 6-18 for the time-series. The 1995-7 and 2001-3 datasets are based on three year averages of the product of a modelling approach developed at CEH which individually models the three components of deposition, wet dry and occult (see 3.2.5b), to create maps of total deposition (see NEGTAP, 2001; Fowler *et al.*, 2004).

Wet deposition is calculated from rainfall sulphate measured by the UK deposition network (Fowler *et al.*, 2004) and rainfall amount. It is modified to adjust for the seeder-feeder mechanism whereby rainfall through hilltop cloud increases pollutant transfer (Choularton *et al.*, 1988) by "*using the ratios of ion concentrations in cloud and rainfall along with an estimate of the extra rainfall amount caused by proximity to hills*" (Fowler *et al.*, 2005).

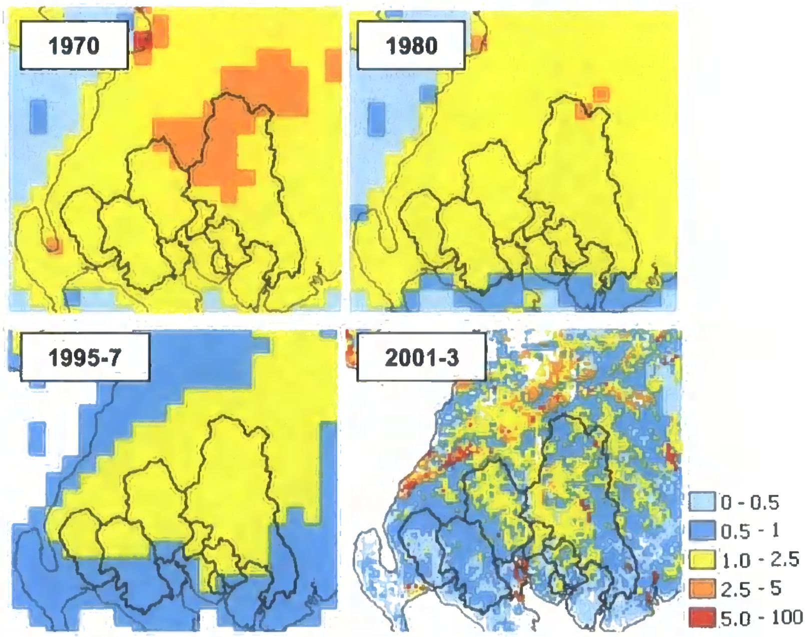
Dry deposition is estimated using the "big-leaf" model (Hicks *et al.*, 1987; Monteith and Unsworth, 1990; Smith *et al.*, 2000) that represents vegetation canopies as a single leaf. Meteorological data such as wind speed, solar radiation, temperature and vapour pressure deficit are used in combination with measured dry-deposition sulphate readings and land-use information to produce maps of dry deposition. Occult deposition is modelled in a similar way to dry deposition and with turbulence and vegetation roughness driving deposition.

It should be noted that there have been a large number of changes to the detail of the models between the 1995-7 dataset and the 2001-3 data. The most significant is increased resolution (from $5km^2$ to $1km^2$) and improved land-use classification; errors are thought to be in the order of ± 20% for wet deposition and ± 50% for dry deposition. Figure 6-18 shows the changing distribution of total sulphur deposition with time. For the 2001-2003 data it is possible to decide to take either an average land-use value for each cell, based on the distribution of land uses within the call, or specify which land-use to use. Following advice from the FCH the worst-case land use scenario (forestry) was used for each cell.

The inclusion of a land-use component within modelling process behind the datasets provided by CEH introduces a need for caution when interpreting the relationships between sulphur and forestry. For regression analyses in Chapter 8 : and Chapter 9 : the 1995-7 dataset was preferred as a) it is the dataset required for use by the *Forest* *and Water Guidelines* b) its lack of spatial resolution prevents it spatially correlating with forestry and thus overriding any forest influence within statistical analyses. Both datasets were used for the maps of Critical Loads exceedance used for stakeholder-based mapping.

The maps 1995-7 and 2001-3 data were provided in a digital format and extracted by catchment into variables named ***"S1995"*** and ***"S2001"*** respectively.

Figure 6-18 Total Sulphur Deposition (source: CEH; units: keq ha-1 yr-1)



6.5.5 Geological Data

Figure 6-19 Galloway 1:625,000 Bedrock Geology (BGS, 2007)

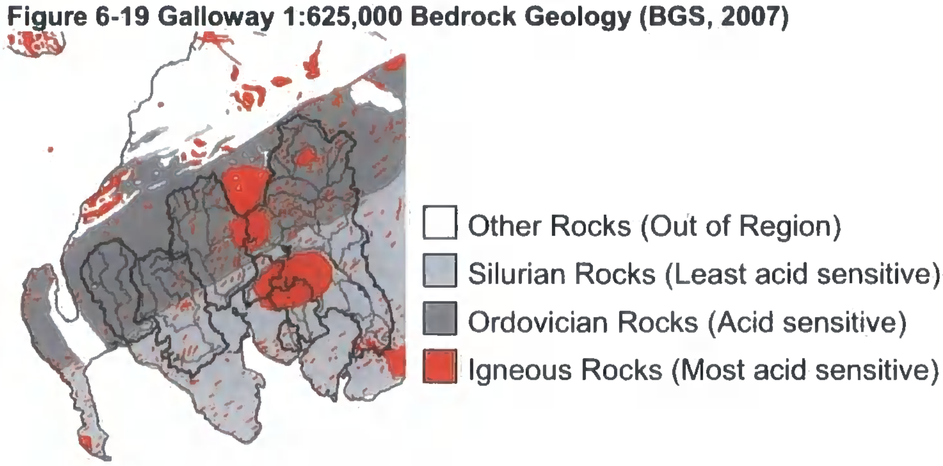


Figure 6-19 shows the geological data for the Galloway region as available from the British Geological Survey in the form of 1:625,000 bedrock geology maps (BGS, 2007). The key geologic units defined used for classifying sensitivity in Puhr *et al.* (2000) were clearly differentiated (Figure 6-19) showing the igneous granites in the Fleet, Cree and western Dee as particular risks. As mentioned in 4.2.2b all these units are defined by the *Forest and Water Guidelines* as sensitive to acidification, although FCH (pers. comm.) reveals that discussions are underway with SEPA regarding the classification of the least sensitive Silurian rocks as a risk; Puhr *et al.* (2000) and GFT (pers. Comm.) also indicate that the buffering in the Silurian sites is better than that in the other two geologies leading to less ecological sensitivity in these areas.

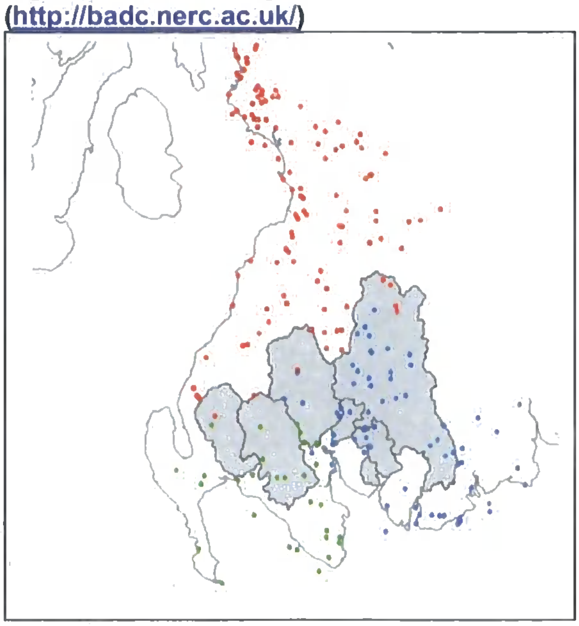
The data were available in a digital vector format and were converted into three $10m^2$ resolution binary rasters of Ordovician, Silurian and Igneous Rocks. These three layers were then extracted by catchment to create variables containing the proportion of each geology within each catchment.

6.5.6 Rainfall

6.5.6a BADC data

Rainfall data were available from the British Atmospheric Data Centre (BADC). The network contains many individual sites of data recorded at a variety of temporal resolutions. For the purposes of this project all available daily and monthly rainfall data for the Kirkcudbrightshire (71, blue), Wigtownshire (31, green) and Ayrshire (121, red) areas were downloaded. A GIS layer was created and any sites outside of the study area were removed from the dataset leaving 104 regionally distributed sites.

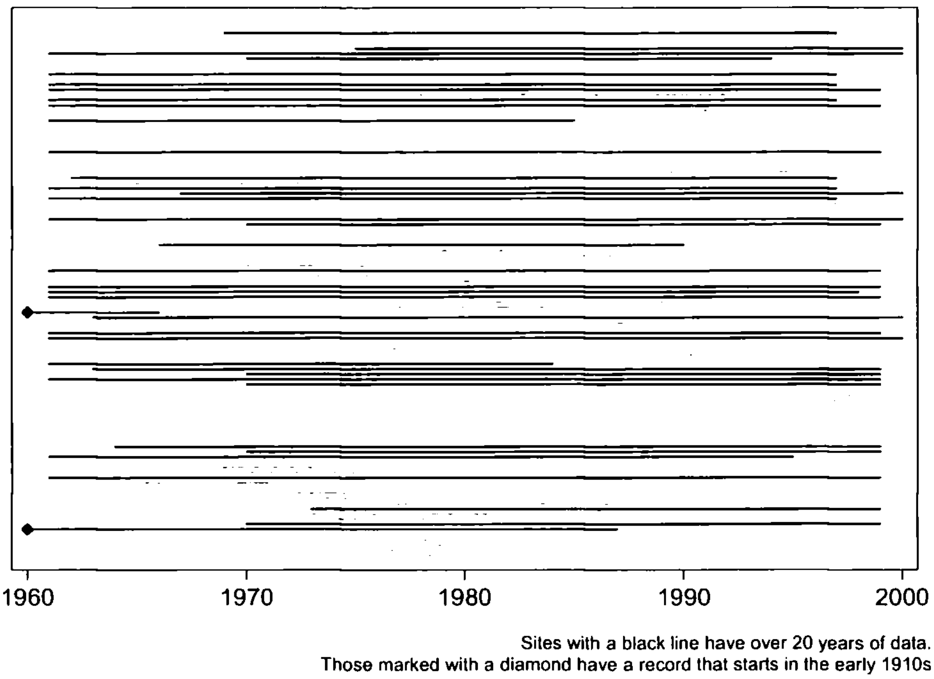
Figure 6-20 Regional distribution of BADC rainfall monitoring sites (http://badc.nerc.ac.uk/)



Three different BADC datasets were included in the study: two sources of daily data (DLY3208 & WADRAIN) and one source of monthly data (WAMRAIN). For more information on the datasets including data collection methodologies see http://badc.nerc.ac.uk/.

The individual downloaded data files were combined into a single Excel spreadsheet, and a macro written to sum the data to annual data. Any years with less than 365 days or 12 months of data were excluded and leap years were adjusted to 365 day years.
Figure 6-21 shows the temporal span of the 103 sites, highlighting the 38 sites with over 20 years of data in bold. The majority of records begin in 1961, but there are two records that date back to the early 1910s (marked with a diamond in
Figure 6-21).

Figure 6-21 Overview: temporal span of rainfall data



The purpose of
Figure 6-21 is to provide an overview of the data available; it makes it clear that despite the large number of sites involved there are significant gaps within the records at many sites. A multiple regression approach was used to reconstruct a full dataset for all locations. This approach worked on the hypothesis that rainfall for a given year was a product of a) the annual variability and b) the impacts of local site factors (proximity to the coast, altitude etc.) which could be represented by the site location. A multiple regression approach was taken whereby each year and individual location was included in the model as a binary independent "dummy" variable, used to predict the dependant variable rainfall. The resulting regression model produced an R^2 of 0.9444 with an RMSE of 111.37 mm/year. Figure 6-22a below shows the Residual Versus Fitted plot for the data showing a close relationship with the X=Y line. There is slight heteroscadasticity around the line and a log linked General Linear Model (GLM; see Cox, 2003) was investigated and found to slightly improve the model (Figure 6-22b; R^2

= 0.965, RMSE 934.304). The inclusion of altitude, easting and northing as additional variables was also investigated but found to provide no improvement over that already provided by the location variables.

6.5.6b Temporal Patterns in rainfall

Inverting either model allows rainfall to be estimated from site location and year. As the GLM provided a slightly better fit than the simple linear regression, it was preferred and a complete, albeit estimated, temporal record from 1911-2000 for the 104 sites within the study area was produced. Figure 6-22 presents the temporal trends in rainfall from 1960-1998.

Figure 6-22 plots the distributions of the raw and GLM-estimated rainfall against one another through time. It is worth noting that the GLM median follows the same trend as seen in the median from the raw data. The two would not be expected to follow an identical trend as the GLM median includes values for all catchments, whether or not raw data are available. The graph indicates that the GLM may have a tendency to under-predict, and that particular attention should be paid to 1996 where the one year upward trend shown in the median of the raw data are not apparent in the GLM estimated median. Nevertheless, the similarity in trend between the two is encouraging; the minimum and maximum predicted values fit very well with the range of the true data. Furthermore, it is clear there has been an increase in the volume of recorded rainfall over the past 40 years; comparison of the means of the periods 1960-1980 and 1980-1998 shows an increase in annual rainfall of the order of 200mm. An examination of the study period shows strong variability in line with fluctuations in the North Atlantic Oscilation (NAO) with the early 1990s and 1998 showing wet weather matching negative NAO index values (Monteith *et al.*, 2000). These NAO fluctuations should be noted as they will have allied impacts on other variables such as nitrate (Monteith *et al.*, 2000), sea salt (Hindar *et al.*, 2004) and acid pulse events (Laudon, 2008).

Figure 6-22 Estimating rainfall for missing years from location and year using regression and GLM approaches to predict missing years from dummy variables for site and year.

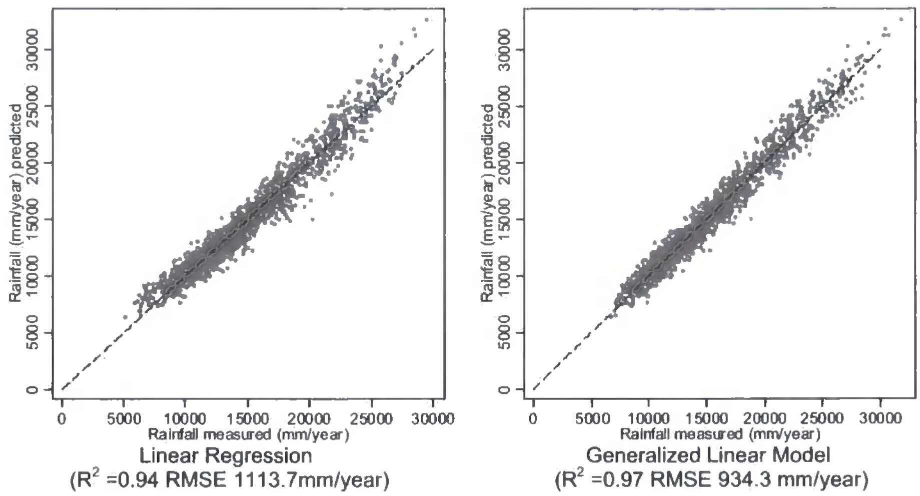
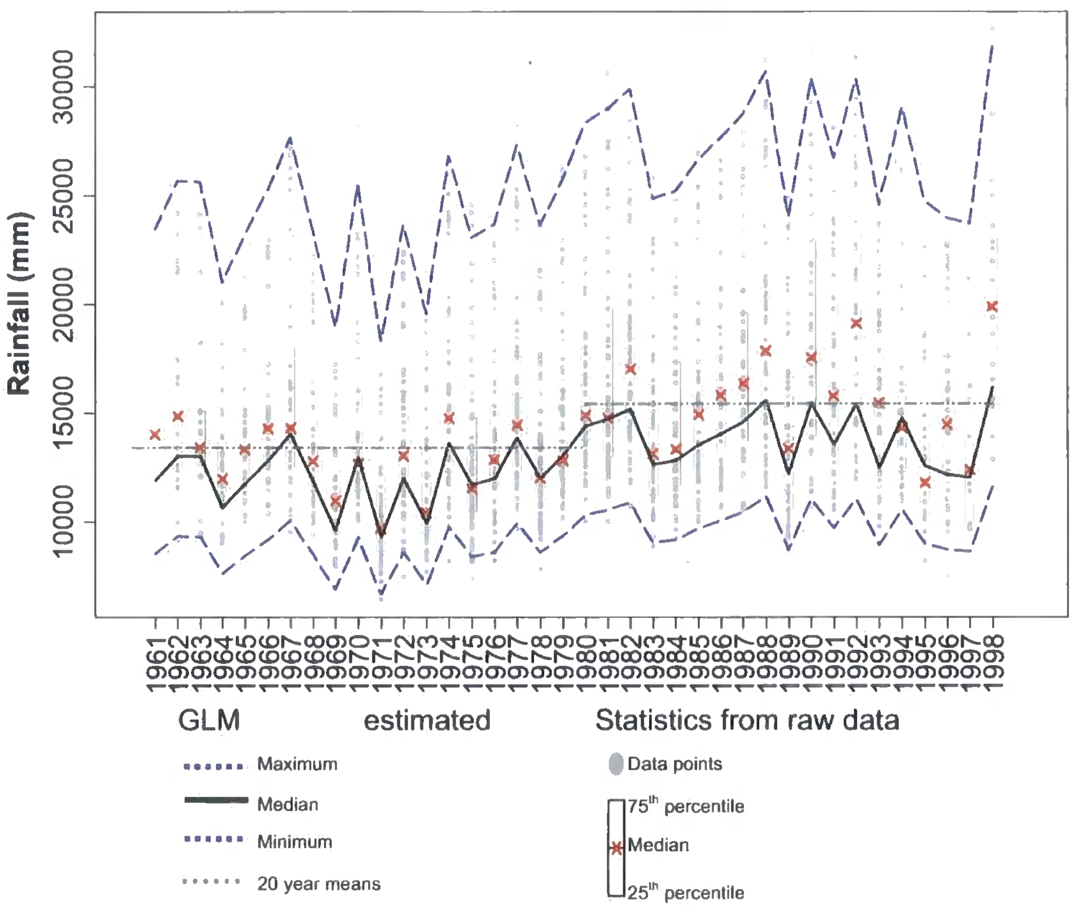


Figure 6-23 Galloway rainfall 1960-1998, reconstructed by GLM in comparison with statistics derived from raw data.

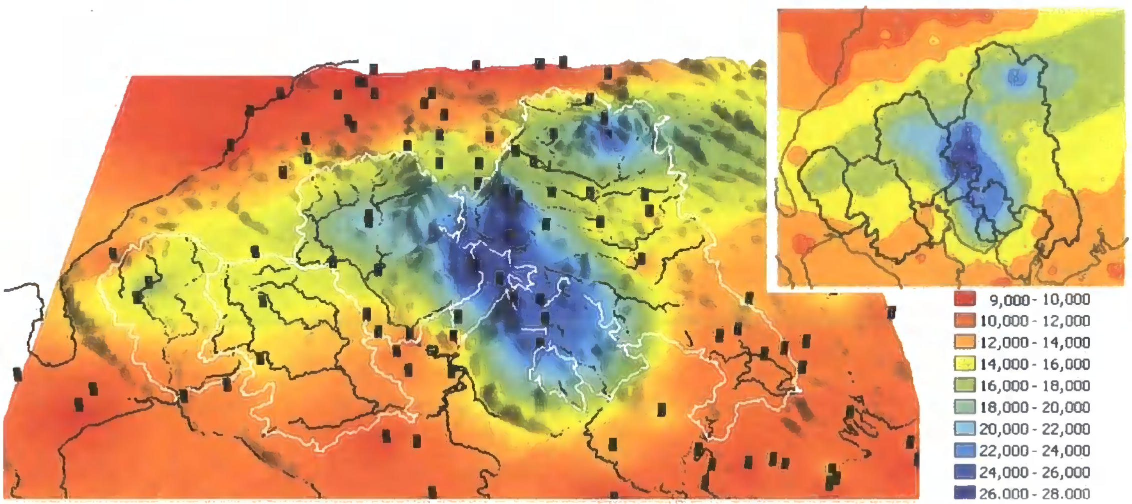


6.5.6c Regional Patterns of rainfall

Although this methodology would allow for the generation of regional maps of rainfall for each individual year since 1960, this was deemed to be beyond the scope of this investigation. Instead mean rainfall for the period 1980-2000 was calculated for each site and exported to GIS as a point layer. 1980-2000 was chosen as it is the period for which the greatest amount of water chemistry data are available and is the focal time-period in Chapter 9 :. The point layer was imported in to ArcView GIS and interpolated to a raster of 100m^2 grid cells using standard Inverse Distance Weighted (IDW) interpolation procedures in ArcGIS. This procedure allocates a value to each grid cell based on a weighted average of the known reference points within a specified vicinity, the more geographically close a known reference point is the greater role it plays in the calculation. As opposed to other methods such as kriging, IDW methods always preserve the values of known points and will not allow them to be replaced even if surrounded by significantly different values.

Figure 6-23 shows that the final map fits well to local geography, with areas of high rainfall matching areas of high altitude. Mean 1980-1998 rainfall data were then extracted for each catchment, using the catchments generated in section 6.5.

Figure 6-24 Spatial distribution of mean rainfall created using an IDW interpolation of the 1980-2000 averages reconstructed using GLM analysis of 103 BADC sites.



Data Source: Extrapolated from BADC data (mm/year)

6.5.7 Altitude

Altitude information was available as the Panorama DEM raster used for catchment generation (see 6.5.2). No additional processing was required and the layer could be directly subset using the catchment layer.

The mean, maximum, minimum and range of altitude within the catchment were calculated as the individual variables "***dem_mean***", "***dem_max***", "***dem_min***" and "***dem_range***".

6.5.8 Additional Data

Easting and northing were also included within the database as a means to map the available data.

6.6 Data Products

Table 6-9 Variables within the catchment-based database.

Dataset	13229 records in total	
Water Chemistry		
(12627 records)	pH (units)	pH
(12180 records)	Chloride (μeql^{-1})	cl
(9543 records)	Sulphate (μeql^{-1})	so4
(11165 records)	Nitrate (nitrogen component of) (μeql^{-1})	no3n
(1319 records)	Dissolved organic carbon (mgl^{-1})	doc
(7140 records)	Calcium (μeql^{-1})	ca
(7116 records)	Magnesium (μeql^{-1})	mg
(9614 records)	Sodium (μeql^{-1})	na
(9475 records)	Potassium (μeql^{-1})	k
(9359 records)	Sea salt corrected sulphate (μeql^{-1})	xso4
(5911 records)	Charge Balance ANC (μeql^{-1})	anc_cb
(5911 records)	Critical Load Exceedance (keq ha^{-1} yr^{-1})	CLoadX
Fisheries data	911 records	
	Salmon fry aged 0-1 years (count)	s0
	Salmon parr aged 1-2 years (count)	s1
	Trout fry aged 0-1 years (count)	t0
	Trout parr aged 1-2 years (count)	t1
	Total fish (count)	Total_fish
	Maximum fish (count)	Max_fish
Forestry Cover	3493 records	
	Average Puhr SWAIH index	SWAIH
	% of catchment under forestry 2-8m tall	CC1
	% of catchment under forestry over 8m tall	CC2
	% of catchment under forestry 2-8m tall over 300m	CC1_o300
	% of catchment under forestry over 8m tall over 300m	CC2_o300
Total Sulphur	All records	
	1995-7 mean catchment S deposition (keq $ha^{-1}y^{-1}$)	S1995
	2001-3 mean catchment S deposition (keq $ha^{-1}y^{-1}$)	S2001
Geology	All records	
	Proportion of catchment on Igneous rocks (%)	ign
	Proportion of catchment on Ordovician rocks (%)	ord
	Proportion of catchment on Silurian rocks (%)	sil
Rainfall	All records	
	1980-2000 mean catchment rainfall (mm/year)	rainfall
Altitude	All records	
	Mean catchment altitude (m)	dem_mean
	Maximum catchment altitude (m)	dem_max
	Minimum catchment altitude (m)	dem_min
	Catchment altitudinal range (m)	dem_range
Other Variables		
	Easting	X
	Northing	Y

6.6.1 Catchment-based database

6.6.1a Creation of the Database

The steps in sections 6.2-6.5 have detailed the process by which water quality and catchment datasets were processed so that information on each is available for both the SEPA and Durham survey locations. All data were tied to location ID fields and were brought together using this into a single database in the statistics package "Stata".

6.6.1b Database contents

The finished database contained 13229 records over the 117 Durham sites and 68 SEPA sites in a format which allowed both single-year regression-based analyses and the analysis of long-term trends. Each record is unique in terms of its combination of location ID, year and the survey from which it was collected; Table 6-9 details the variables within the database as they area available for further analysis in Chapter 8 : and Chapter 9 :

6.6.2 Stakeholder-Based Mapping

6.6.2a Methodological Approach

The following section details the approach by which the viewpoints of areas at risk of acidification presented by SEPA, the GFT and the Forestry Commission were presented as maps for the stakeholder discussion process. It should be noted that it was the first time that FC Critical Loads maps had been created for Galloway, and as a result the first time that stakeholders had had the opportunity to see the extent of the areas identified as at risk by this methodology. This was also the case for some stakeholders regarding the fisheries data, as due to the reluctance of the GFT to release the data (Cf. 5.3.1a(ii)), many other Galloway stakeholders, particularly within SEPA, had not previously had access to them (see 5.3.1c).

6.6.2b SEPA Water Body Classification

To represent the SEPA viewpoint, the results of the preliminary WFD water-body characterisation for Galloway was used (Environment Agency and SEPA, 2005). This classifies all water bodies within the area in terms of the factors affecting their potential to meet the demands of the WFD and identifies the pressures on these systems and the industry sector responsible for the pressures. Acidification is represented in the SEPA coding system as a site with a "diffuse pollution" pressure which is attributed to both "electricity, gas and water supply" and "forestry, logging and related activities" or "agriculture and forestry". All sites matching these descriptions were identified, and their reporting category from 1A, "likely to fail the good status targets of the WFD" to 2B, "likely to meet the good status targets of the WFD" was used to code the rivers. The classifications were made using pre-existing data at the time of the characterisation exercise and drew on invertebrate and diatom data as they were seen to be "the most vulnerable indicator species"; fish data were not used in the classification (7.2.1c.).

The presented map (Figure 7-2) therefore represented the best available information at that time on the areas identified by SEPA as those in which forestry's role as enhancing acidification was identified as being at risk of contributing to a water body failing the "good status" needs of the Water Framework Directive.

6.6.2c Fisheries Trust Data

The GFT was consulted regarding how best to present its data and a simple classification based on the presence and absence of salmon and trout species in 0+ and 1+ age classes was selected by them. Data from 2000-2005 were used and the best-case scenario was selected. Four levels of classification were selected; the top level of fish health required the presence of both 0+ and 1+ fish for both salmon and trout, the next level showed evidence of salmon at the site, irrespective of trout, the third level showed no evidence of salmon presence, but trout present and the worst level showed no fish of any type. Consultation with the GFT was then used to identify sites where the fish health presented was perceived to be greater than that expected as a result of fish stocking. These sites were downgraded in terms of the colour they were mapped in, but retained the letter so that the presence of salmon was not denied.

6.6.2d The Forest and Water Guidelines view of risk

As discussed in section 4.2.2 the approach taken by the *Forest and Water Guidelines* as a means of determining the areas in which forestry contributes to a risk of acidification is twofold: i) is the area over 300m or in a special area of conservation; and ii) does the area fail a Critical Loads exceedance test?

Two data layers were presented to reflect the effect of these decisions in practice. The first Figure 7-8 shows forest cover in 2005 as predicted from satellite images in section 6.5.3d with the 300m contour overlaid. All areas under 300m are greyed-out, with the exception of the Bladnoch catchment which is, although entirely below 300m, covered by the *Forest and Water Guidelines* due to its status as an SAC. This leaves a map with white areas where Critical Loads tests would be necessary and grey areas where the *Forest and Water Guidelines* do not apply. The inset in this diagram shows the study catchments coloured by the proportion of forestry over 300m: only areas indicated in orange and red currently have over 30% forestry over 300m; it is only in these areas that the *Forest and Water Guidelines* would expect a "forest effect".

The second layer reflects the results of the Critical Loads model as applied to the water chemistry data collected in 2006. In consultation with the Forestry Commission Hydrologist it was agreed that four Critical Loads scenarios (Figure 7-5) would be shown to indicate some of the variability resulting from the selection of a) the ecological sensitivity of the model as represented by the ANC_{LIMIT} buffer value and b) the precautionary approach taken in the *Forest and Water Guidelines* by using the 1995-7 total S deposition dataset in place of the most recent 2001-3 maps of total S deposition.

The Critical Loads model (Appendix A) was run using the field data collected in 2006 (6.2) using both the ANC value of 0μeql^{-1} recommended by the *Forest and Water Guidelines* and a more precautionary value of 20 μeql^{-1}. In addition these two ANC scenarios were repeated using the 1995-7 and 2001-3 total S deposition datasets (Table 6-10).

Table 6-10 Critical Loads exceedance scenarios for the stakeholder-based mapping

Scenario	ANC value	Total S Deposition	Water Chemistry
1	0	1995-7 (S1995)	Durham 2006
2	0	2001-3 (S2001)	Durham 2006
3	20	1995-7 (S1995)	Durham 2006
4	20	2001-3 (S2001)	Durham 2006

Of these scenarios "Scenario 1" represents that of the *Forest and Water Guidelines*; this scenario was applied to the entire contents of the catchment-based database to produce the variable "***CLoadX***".

6.7 Conclusion

This chapter has focused on the methods by which available data from a number of national organisations (SEPA, BADC, CEH) and private stakeholders (GFT, University of Durham) were combined with satellite image datasets to create products to answer research questions associated with this thesis. Both qualitative maps of data for stakeholder-based discussion and a quantitative database of catchment-based information were created.

The fact that the majority of these products are based on existing data stresses the repeatability of the approach to other areas and stresses the importance of making use of the best available data sources. The utility of satellite imagery as a source of long-term land use data for catchment-based studies should not be overlooked. An understanding of long-term water quality records for any site necessitates a comprehension of the changing impacts of the land use within the catchment. As the Water Framework Directive introduces the need for holistic river basin management plans, satellite imagery may provide key information on forest structure in addition to simply forest cover, data which may be invaluable to determining forest impact. This will be particularly true in areas beyond those owned by the Forestry Commission for which detailed information about the planting age and extent of planting is not available.

The chapters that follow draw on the products produced here to focus on the key questions of this thesis by: a) focusing discussions on the implications of forestry policy to Galloway (Chapter 7 :); b) investigating whether or not there is a "forest effect" beyond that recognised in the *Forest and Water Guidelines* (Chapter 8 :) and c) determining if a "forest effect" on the recovery of freshwaters can be identified (Chapter 9 :).

Chapter 7 : Discussing Stakeholder Knowledges

7.1 Discussing Available Knowledge

7.1.1 Introduction

Chapter 6 detailed the methodology by which maps of the viewpoints of the key stakeholders were generated. This chapter focuses on a stakeholder meeting organised within this thesis during which these maps, and the Critical Loads model in general were discussed. The aim was to draw on "participatory" techniques to allow all stakeholders a chance to discuss the various datasets which mapped their viewpoints and contributed to their decision making. There has been much research focussing on "participatory" mapping or GIS (Harris *et al.*, 1995; Tir Coed, 2000; Bojorquez-Tapia *et al.*, 2001; Carver, 2001; Rambaldi and Callosa-Tarr, 2001; Nakicenovik, 2002; Minang, 2003; Dougill *et al.*, 2006; Reed *et al.*, 2008). The aim of this research is to more equally distribute the power/knowledge (Foucault, 1973) inherent in the mapping procedure; by mapping/classifying an area it becomes something that can be controlled. The participatory process aims to involve the stakeholders "mapped" as well as those involved in the "mapping" as a means to subvert this process and allow a more equitable debate with a greater opportunity for the inclusion of local knowledge.

Within this project my aim was not to subvert power relationships but to observe them and the way they affected knowledge transfer. In presenting the results of the stakeholder meeting this chapter focuses on the overall question of the thesis to determine: *to what extent does inter-stakeholder discussion of mapped "forest effects" influence the inclusion of different knowledges in forestry policy and practice?*

7.1.1a Subjectivity, again.

As I stressed at the end of chapter 2, this thesis aims to achieve rigorous subjectivity; my interpretations of the events that took place at the meeting are necessarily my own. A meeting is a far more dynamic event to interpret than published reports and recorded interview transcripts (although the meeting was recorded and the transcript was used). The potential of my positionality to influence the findings was considerably increased due to my position as an active participant and chair of the meeting. Furthermore, contextual factors such as the other stakeholders within the room may influence the views that stakeholders are willing to express.

To ensure the most robust interpretation possible, I base my analysis on quotations transcribed from the meeting and the agreed meeting minutes (Appendix G). The meeting was run like an official business meeting and I, based on my participant experience with these stakeholders, and conversations with them individually after the meeting, do not believe that the established relationships between the key stakeholders prevented their opinions being expressed.

It should, again, be noted that the maps presented, particularly the Fisheries Trust data and the Forestry Commission's Critical Loads maps were newly presented datasets. The Fisheries Trust data had never been seen processed in this manner, although the Galloway Forest District Manager (FC-G) had seen fisheries data when the other stakeholders had not (see 5.3.1b(iv)). Similarly the 2006 Critical Loads exceedance Maps had not been shown prior to the meeting. It was not, however, the first time that stakeholders were exposed to regional Critical Loads maps in general; the maps for 2005 maps had been disseminated the year before, but were to be treated with caution until the laboratory sulphate issue had been resolved (see Chapter 6). To avoid any confusion only the 2006 maps were discussed at the meeting.

7.1.2 The Meeting: Participants

Table 7-1 Stakeholder Meeting Participants

Local/National	Science/Practice	Organisation	Participant
L/N	S	University of Durham	Myself
Long-term project Key stakeholders			
N	S	Forestry Commission	Forestry Commission Hydrologist (FCH)
L	P	Forestry Commission	Galloway Forest District Manager (FC-G)
L	S	Galloway Fisheries Trust	Senior Fisheries Biologist (GFT)
L	P	SEPA	Head of SEPA Newton Stewart (SEPA-NS)
Additional Specialists			
N	S	SEPA	SEPA Ecology Unit Manager *(SEPA-Ec)*
L	P	SEPA	Local SEPA representative *(SEPA-1)*
L	P	Forestry Commission	Forestry Commission Conservator *(FC-C)*
Additional Interested Parties			
L	P	SEPA	2 additional local SEPA staff members
L	P	GFT	1 additional GFT staff member
L	P	GFT	1 local GFT interested party (***not*** GFT-S)
L	P	FC	1 additional FC staff member

The meeting was held on August 31st 2006 at SEPA headquarters in Newton Stewart and had twelve participants (Table 7-1). The four key stakeholders representing Forestry Commission Policy/Science (FCH), Galloway Forest Management (FC-G), Local Environmental Regulation (SEPA-NS), and local fisheries concerns (GFT) were present. It should be noted that SEPA-NS as the key SEPA stakeholder following SEPA-G's retirement. SEPA-G and GFT-S were both invited to the meeting but neither was available.

Two additional specialist stakeholders were also invited following consultation with the other members of the group. First amongst these was a Forestry Commission Conservator (referred to as *FC-C*) responsible for managing private forestry plans in the Bladnoch. It should be noted in terms of context that this stakeholder was new to the core group, and was in the presence of two senior members of staff (Forestry Commission Hydrologist and Galloway Forest District Manager). The second addition was the Unit Manager for the SEPA Ecology unit (referred to as *SEPA-Ec*). This stakeholder provided specialist scientific knowledge for SEPA as well as a detailed knowledge of the SEPA approach to the WFD. One local SEPA representative (referred to as SEPA-1) also contributed to the debate.

7.1.3 Format of the meeting

The meeting was organised to be similar in focus to a normal business meeting. I took the role of chair and the meeting room at Newton Stewart was used to host the meeting. The agenda of the meeting was as follows: -

- Introduction (R Dunford)
    1. An Introduction to the Critical Loads model (informal with questions) (FCH)
- Lunch
    2. Galloway and Acidification (Open discussion around maps) (R Dunford)
        a. SEPA's WFD Characterisation
        b. The 300m rule
        c. Critical Loads exceedance
        d. Fisheries data

A summary transcript of the meeting is available in Appendix I.

7.1.3a Impacts of the methodological approach

It is important to briefly discuss the potential impacts on the results presented of the approach taken.

In the first half of the meeting the Forestry Commission Hydrologist explained in detail the Critical Loads approach. This was presented as a power point presentation discussion of key points was encouraged and occurred. The rationale was to assure that all stakeholders had both, the opportunity to be at a similar level of knowledge regarding the Critical Loads approach, and to ask questions directly to the scientist responsible for integrating the Critical Loads model into the *Forest and Water Guidelines*.

By using a presentation format it is acknowledged that power is automatically given to the presenter; the FCH was put in a position of the knowledgeable authority and given greatest control over the format. This is not seen as a problem for the purposes of this study, as this would be a perfectly normal practice within an inter-organisational meeting. It is however recognised that the approach taken may influence the views expressed and influence the willingness of individuals to speak and express their views. Furthermore it is recognised that other factors that influence the transfer of knowledge may have remained unsaid, or may indeed include the unwillingness of parties to speak. This project focuses on the factors that stakeholders feel strongly enough about to raise for discussion.

For the second half of the meeting each stakeholder was provided with 12-page A3 booklets containing the maps presented below. A similar colour coding system was used for all maps to aid rapid interpretation. I introduced each map explaining where the data were from and what they represented, and gave the owners of the data a chance to explain the dataset; any queries regarding the format or data were also answered. Each map was then opened up for general discussion. As many of the factors that would influence the inclusion/exclusion of knowledge would revolve around the relationships between stakeholders I remained as 'neutral' as possible and contributed my own knowledge only when asked. As chair I ensured that questions raised by stakeholders were answered, and stimulated discussion when I felt there might be an additional viewpoint to express: this was only ever done using neutral questions such as "do fisheries/local forestry/SEPA have a viewpoint on that?" to allow stakeholders the opportunity of withholding views if desired. In practice my interpretation of the discussion is that it was open and free-flowing and the key points of discussion as I understood them were discussed.

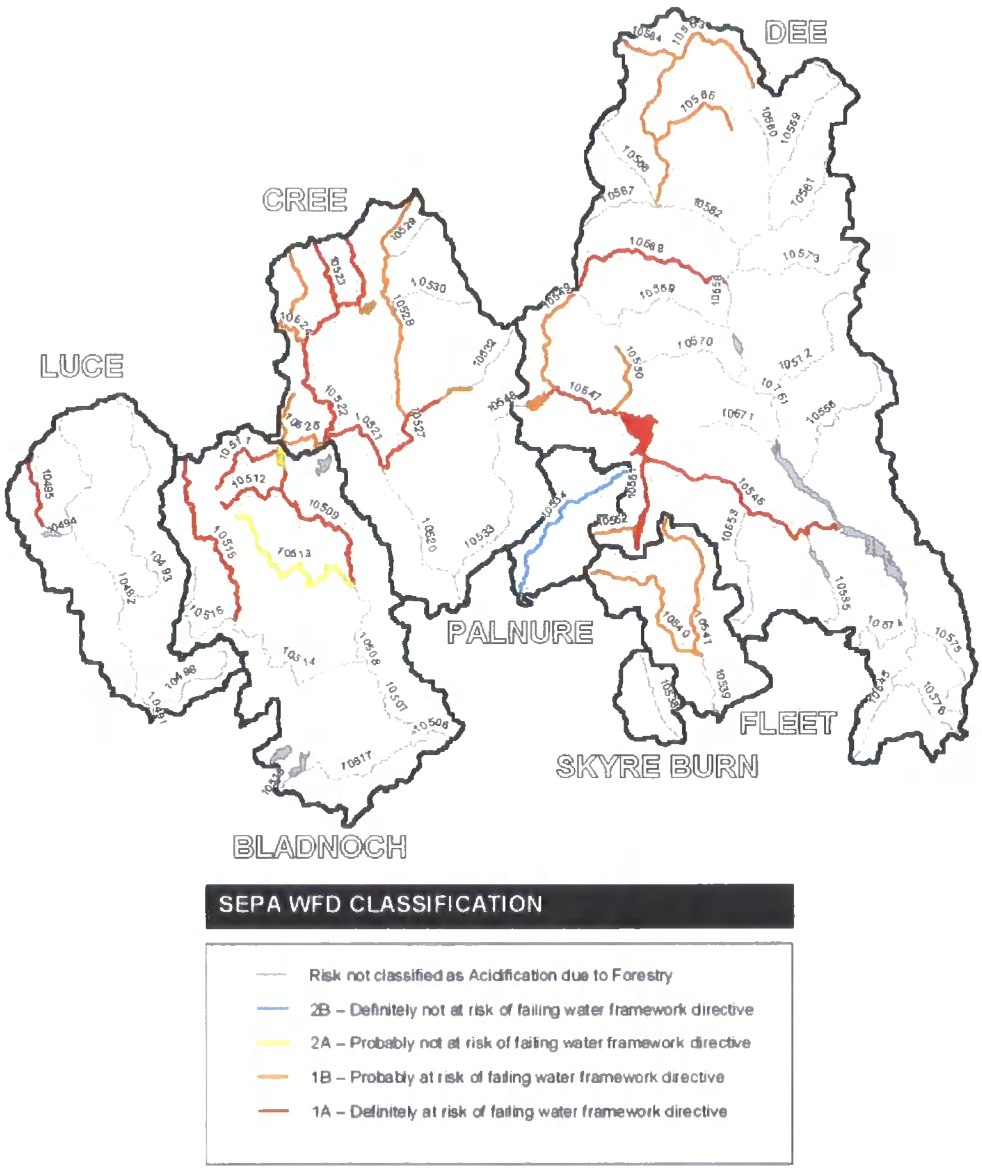
The following sections draw out the major themes highlighted in the discussion; the format of the meeting itself is not followed, but any potential impacts of the order of events on the interpretation of stakeholder views will be discussed in context.

7.2 The meeting

7.2.1 Ecological Risk

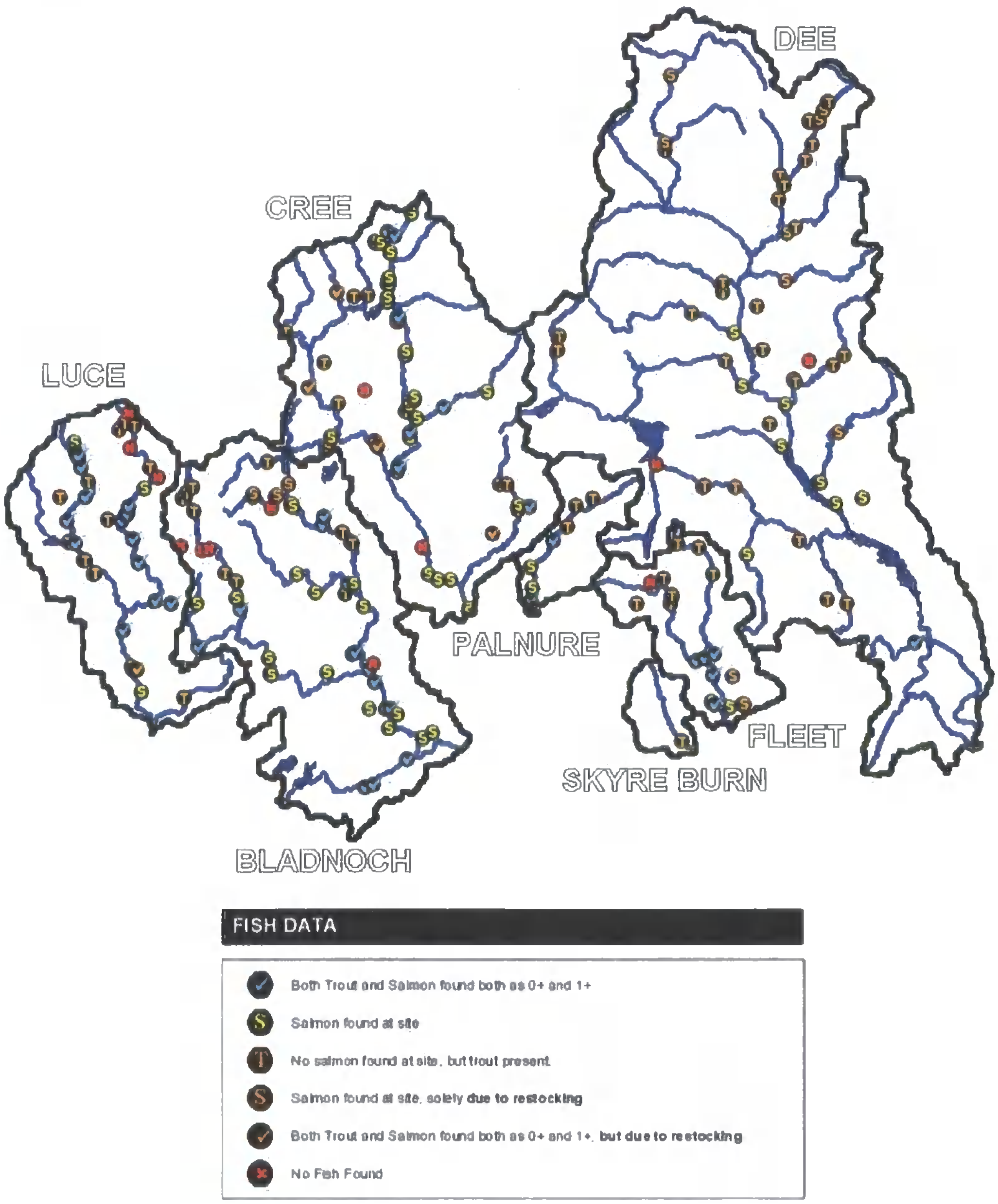
7.2.1a The Maps

Figure 7-1 SEPA Water body Classification mapped following Scottish Environmental Protection Agency, 2007.



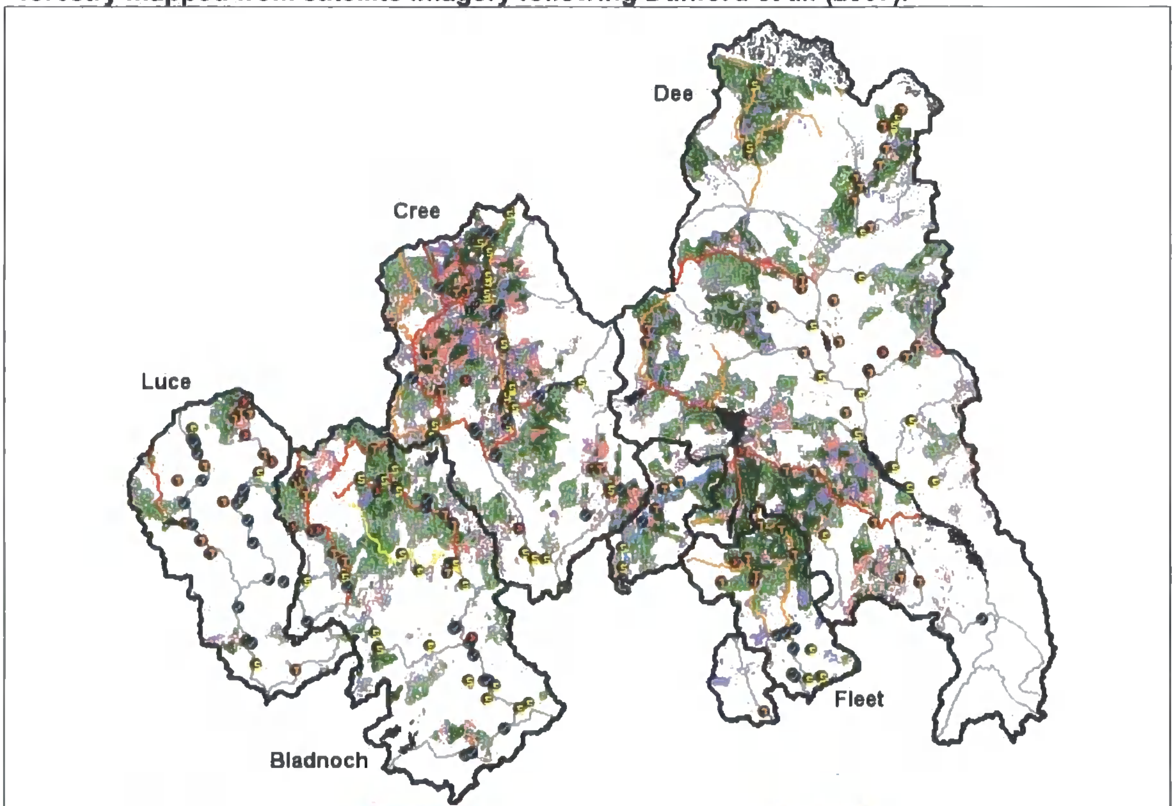
The first of the datasets to be discussed during the open discussion was the Scottish Environmental Protection Agency WFD characterisation of areas at risk from exacerbated acidification due to forestry (the "forest effect"). This layer was chosen as it presented the view of the highest level of legislation, the EU Water Framework Directive. SEPA's ecologist stressed that the layer only showed initial *characterisation* and aimed to target monitoring rather than being the final *classification* of risk. The layer is characterised drawing on "existing" data regarding the "most sensitive elements" to a given pollution; in the case of acidification these are diatoms and invertebrates. No fish data are included. Figure 7-1 shows the map presented at the meeting. The processing steps required to create the file are discussed in section 6.3.1).

Figure 7-2 Fisheries status in Galloway. Drawn from Galloway Fisheries Trust 2000-2005 electrofishing data and classified following a methodology selected by the GFT themselves to highlight risk in terms of the presence/absence of fish species and life cycle stages.



The second ecological dataset presented was that of the Fisheries Trust's fish data. This was the last dataset discussed in the meeting, and put at the end so as to refocus the discussion on the differences between modelled risk and ecological data (discussed below). The processing steps required to make the map are described in section 6.4 and are based on the presence/absence of salmon and trout at various age classes, and modified by the GFT where the ecological status is only good due to active restocking. The Fisheries Trust were very keen to stress the dangers of interpreting presence or absence of trout as an indicator of health: *"[it] is one to be very careful about, because the literally if it only takes a single trout to trigger [decision making and it needs to be recognised that] ... there is a big difference between what would appear to be a semi-natural population and a heavily impacted one, because there's hardly anywhere that there isn't trout to be honest with you*" (GFT). Figure 7-2 shows the data as presented at the meeting.

Figure 7-3 from Galloway Fisheries Trust 2000-2005 electrofishing data and classified following a methodology selected by the GFT compared with changes in closed canopy forestry mapped from satellite imagery following Dunford *et al.* (2007).



	Non-forest		Forestry felled 1995		Forestry felled 2005
	Forestry establishing 1989-2005				Established forest

7.2.1b Interpretation

Before moving on to the stakeholder discussion of the datasets it is important to briefly consider the spatial distribution of data presented in the maps above in light of the wider interpretation of the "forest effect" presented in chapters 4-5. Figure 7-3 presents the ecological data overlaid on the forest change map from chapter 6 as context for a qualitative interpretation of the "forest effect". This map was not presented at the meeting but is used here to guide interpretation of a wider "forest effect".

The first point to note is that both the Fisheries data and the Scottish Environmental Protection Agency diatom and invertebrate based characterisation continue to highlight problems in the lowland Bladnoch, Cree, Luce and Fleet. With regards to the Bladnoch the entire catchment is below 300m; whilst the western tributary (the Tarff) shows only the presence of trout, the eastern tributary (the Bladnoch) has significant spatial variation in fish population health. The Cree, however has experienced significant deforestation, some of it a year or two earlier than usually planned felling (FC-G, pers comm.) and although characterised by SEPA as at risk, shows signs of salmon and healthy fish populations on the eastern tributary (the Minnoch) and some evidence of salmon in the main Cree; although there remain some burns with only trout. The Luce shows for the most part a healthy fish population in its moorland streams, but unhealthy fish populations towards the north (cross water of Luce) in an afforested area; these problems are not identified in the SEPA classification of the "forest effect". Threats to good ecological status are identified in terms of both fisheries data and SEPA characterisation in the upper Fleet. In this area, acid sensitivity is greater as there is an igneous plug beneath the northern Fleet (Figure 7-6), however the Fleet has very low proportions of forestry above 300m (Figure 7-8) and so a "forest effect" is not expected under the mechanism-down view. The Dee is a large catchment in which SEPA characterisation of risk matches well with the Fisheries Trust data.

7.2.1c Stakeholder Discussion: the inclusion of Fisheries Data within SEPA

It is clear from the images above that the fisheries data provides significantly more spatially detailed information surrounding areas at risk than the SEPA characterisation. This is partially due to the national scale reporting nature of the SEPA approach. The actual characterisation draws on a multiple sites within a classified water body; the eastern Cree tributary (the Minnoch), for example, is classified based on "*a couple of different chemistry sites and a range of different ecology sites*" (Local SEPA representative: SEPA-1). It is important to note, however, that the existence of locations of fisheries impacts outside of the SEPA characterisation areas (such as the northern Luce) and the evidence of recovery in areas highlighted as at risk by SEPA (such as within the Cree) suggests that additional benefits could be gained by the inclusion of fisheries data within SEPA's classification approach.

This was raised as an issue for discussion by the Fisheries Trust stressing that they were waiting to be asked for consultation by SEPA regarding the WFD: "*nothing has come out yet for a consultation because we're waiting to input to that to suggest that the information that's held for a region like this should be input*" they add that they see this as particularly important as the WFD classification "*has potential to input to bits of* *the Forest and Water Guidelines as well*". They acknowledge that their assistance has been sought regarding the WFD surveillance network set up by SEPA but express surprise at the "*lack of sites*" it contains arguing that the data from it is going to be "*very limited*".

The head of the SEPA Ecology unit explained that the purpose of the network was to "*monitor long-term trends*" for the purposes of the WFD and target specific pressures so as to work as different reference conditions for the varied statuses from high to poor. Local scale monitoring that defines classification, in terms of acidification would not draw on fish data; it would instead focus on invertebrates and diatoms, as these were seen to be more sensitive.

The Fisheries Trust however stressed the data they possessed that was picking up recovery of fisheries in some areas "*we're seeing spawning in the salmonids in the most sensitive stage in the Cairnefore ... and we are picking up the 1s and 2s of salmon in places where we hadn't before, and [we] picked up some spawning in the high Cree*". They argued that they were in possession of detailed habitat survey data for all rivers, which they would be keen to integrate with SEPA "*we've done habitat surveys, they've all been done, I don't know how from a SEPA point of view how we can try and that sort of data can feed into it, because there is a lot of time and money that has gone into it to try and help feed into forestry and help take things forward and it would be nice if it could fit into forestry*".

The response from the head of the SEPA Ecology section was to question whether the methodology followed was that put forward by the WFD "*there have been methods developed for looking at habitat morphology; it's largely based on habitat survey but it goes further than that*". The Fisheries Trust agreed that their approach was different.

With reference to the openness of SEPA to outside data as raised by the GFT in section 5.3.1c, it should be noted that no action was taken to encourage greater inclusion of fisheries data for the purposes of the WFD. The reasons for this are unclear but may include a) the differences in methodological approach, b) the decision as to what data best classify risk, c) the practical aspects of dealing with a vast number of datasets for decision making purposes, d) perceived problems with taking a more qualitative and holistic view of the varied datasets and their problems or e) other unmentioned factors. Whichever reason results in the exclusion of the fisheries data by SEPA at a policy level is therefore a potential factor providing a barrier to the transfer of knowledge: how significant this is for SEPA as the environmental regulator will depend on the nature of the "forest effect" and the utility of the additional data to help address it.

At the local scale, there was greater interest within SEPA to include data. Local SEPA staff members suggested that "*it would make sense to share data*" with the GFT, acknowledging that "*we don't have any fisheries data*" (SEPA-1) and offering their chemistry data in exchange. The new head of SEPA Newton Stewart stressed that it would be particularly helpful if the GFT could provide SEPA information on where there were signs of recovery.

The local Galloway Forest District Manager was also very pleased to see the fisheries data, "*this is a really neat presentation; it's very very good*" and demonstrated his existing knowledge of the dataset by asking "*were there not more red crosses in the past?*". He stated "*it's not clear where to target; some streams are inaccessible to salmon; what would be useful would be to have a map of this. That would help me to analyse this information.*"

The GFT agreed to help both the FC and local SEPA representatives with these requests. The action points from this discussion were therefore a) for the GFT and local SEPA to work together to provide the local Forestry Commission maps to identify areas where they thought recovery was underway b) to organise a meeting for all parties to review the existing monitoring work in order to "maximise data value" (see Appendix G). It is clear that the factors that produce a resistance to knowledge exchange between local stakeholders and policy are less significant for other local stakeholders with similar levels of interest in regional problems; as a result forestry practice is once again (Cf. 5.3.1b(iv)) shown to be more open to influence than policy.

7.2.2 Critical Loads exceedance Maps

7.2.2a "An Introduction to the Critical Loads approach"

Before discussing the maps produced of Critical Loads exceedance it is important to introduce the main topics raised in the discussion during the Forestry Commission Hydrologist's presentation introducing the Critical Loads approach. In addition to introducing the general concepts behind the Critical Loads approach and the choices made by the FC when following this method (explained within this thesis in 3.2.6a) two key themes of relevance were pre-empted for the afternoon's discussions: these were a) the issue of non-forest exacerbated acidity and b) the modification of the ANC_{LIMIT} as a means of better matching the model to ecological data.

7.2.2a(i) The issue of non-forest exacerbated acidity

The issue of non-forest exacerbated acidity has been raised as a potential issue earlier in this thesis (4.3.1d). In the debate that follows it becomes the cornerstone of the defence of the *Forest and Water Guidelines* mechanism-down conception of the "forest effect" in the face of ecological data: during the presentation it was introduced as the reason behind the selection of the Critical Loads model as discussed in 3.2.6a.

"*The great value of the Critical Loads approach is that the critical load allows you to quantify the sensitivity, the buffering in the system and then compare it with the amount of load of pollutant that that system has received, and you're using the same units so you can determine if that system is exceeded or not. If you just went out and did a simple characterisation of a water course based on geology or pH or whatever and said all these waters less than pH 4.8, 4.5 are obviously subject to acidity therefore they are at risk, well ok they may be at risk, they may be acid sensitive but that doesn't say whether the loading to that system, the pressure that's being put on it in terms of acid deposition is actually sufficient enough to be acidifying that system to be tipping the balance; its only if the loading exceeds the critical value that you will get further acidification and damage; and the value of this approach is that it allows us to put these things together.*" (FCH)

At its core is an argument repeated consistently in the debate that follows: areas of impact where deposition is not high are areas of non-forest-exacerbated acidity where the agreed "forest effect" does not apply, and as such changes to forest management will not contribute an ameliorative effect. The use of the term naturally acid is ambiguous as it does not differentiate between a) pristine conditions with no deposition and no forest impact and b) conditions in which there is no "forest effect" but deposition still influences acidity. To separate the two the term "non-forest exacerbated acidity" is used below to specify the second meaning.

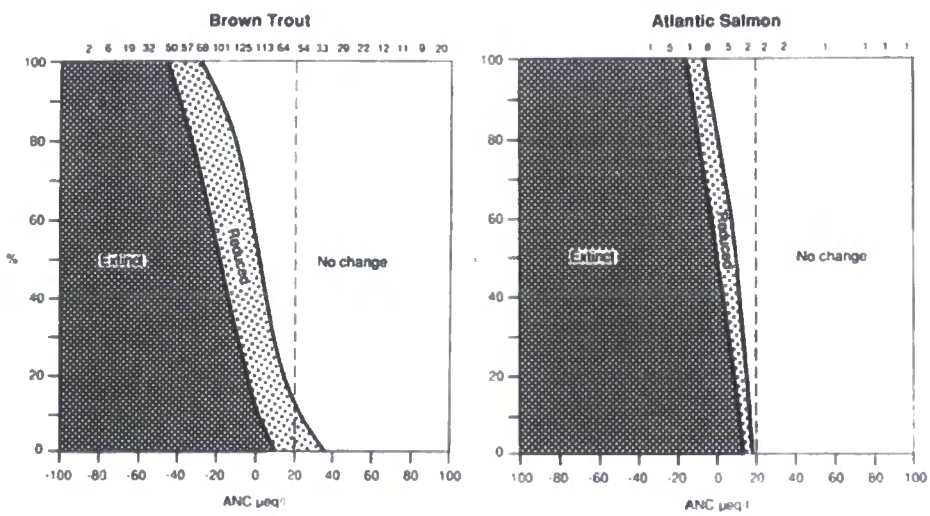
7.2.2a(ii) The choice of ANC_{LIMIT}

The second issue pre-empted during the introductory presentation was the issue of the ANC_{LIMIT}. Salmon and Trout ANC response curves from Lien (1996: Figure 7-4) were shown as discussion topics and the Forestry Commission Hydrologist himself raised the issue of the ANC value to select. As discussed in section 3.2.6a the Forestry Commission use a value of ANC=0 for their Critical Loads (and Critical Loads exceedance) calculations, the Forestry Commission Hydrologist discussed this in terms of its implications for ecological survival:

"*we selected a value of zero and you may think 'well that's not a very good value; there's a forty percent probability that trout are reduced and there's a ten percent likelihood that they become extinct and therefore we should chose a higher value, maybe +20, where 90% of sites showed no change and 10% showed a reduced population.*"

The Forestry Commission Hydrologist justifies the *Forest and Water Guidelines* use of zero based on the fact that the samples are taken at high flow rather than median flow for which the ANC:Fish curves were generated. He argues that "*the reason we selected zero was because we were applying this calculation to high flow samples and we find that ANC varies with flow and at high flow we have lowest ANC values*" and that as the difference between high flow ANC and median flow ANC "*is much more than 20 its 30, 40, 50 or more in many cases*" that the approach is therefore not only appropriate but precautionary: "*we think we've taken an appropriate and in any case precautionary value to select for these high flows.*"

Figure 7-4 ANC Response Curves from Lien *et al.* (1996) showing the percentage chance of damage to Trout and Salmon with changing ANC levels.



The Forestry Commission Hydrologist argues that "*If we were going to base it on mean chemistry then the 20 would certainly be a preferred value for us to use*" recognising that it is the value used by both the UK Critical Loads advisory group and DEFRA for reporting to Europe "*because they're basing it on mean chemistry*". He argues that they have chosen to go for high flow samples as "*it's seen as being the most sensitive stage, and makes it easier in terms of when to assess ... the system when it's most acid sensitive*".

The Fisheries Trust questioned the geographical origins of the data behind the ANC curves "*have there been Scottish studies done regarding the trout related to ANC?*". The Forestry Commission Hydrologist replied referencing the work of McCartney *et al.* (2003) that Scottish studies had been done and that they confirmed "*similar relationships*" where "*zero [ANC] and below he found most fish were more or less extinct ... and he was advocating 20 as a value for low DOC waters. He was basing that on mean chemistry, and he did show that the difference between minimum and mean ANC was 50 or more*". This is not, strictly speaking, a true reflection of the work in McCartney *et al.* (2003) which identified some sites where the difference between the two was as low as 18 μeql^{-1}, however, for Galloway sites (where McCartney *et al.* found a mean difference 59 μeql^{-1}) it was reasonable[20]. The Forestry Commission Hydrologist argued that the best approach would be to tailor the ANC curves to local conditions suggesting "*we could look at that in more detail in Galloway for instance, and see what relationships we get*".

This suggestion was one with which the Fisheries Trust were happy to agree "*I think that would be very useful; there is a huge genetic difference between salmon and trout with their susceptibility to acidification*" they argued that a) the use of a response curve rather than presence and absence "*we've hardly found anywhere where there is an absence [of trout], nearly all the catchments populations are present but we would suggest that they are seriously impacted there's only one or two older individuals so its quite a big assumption*" and b) the study of salmon in the place of trout would be vital as "*brown trout are definitely the last species to die out so if its being used as the critical one then we're going to lose all these other species first you're accepting the extinction of all the other species and its only the very last species you're trying to save.*".

The Forestry Commission Hydrologist referred to the ANC response curve for salmon and argued that, compared with trout, "*the salmon response curve it was similar in some respects but much narrower in terms of it's a much sharper response between no effect and effect*" and that whilst this meant that whilst it was more sensitive in ANC's below 15 it showed the same protection from acidity in waters of ANC 20 "*if you select a value of 20 that will still be no change...albeit that the response curve is based on mean chemistry and are argument is that a value of zero is appropriate for high flow*

[20] McCartney *et al.* (2003) show that of the six sites at Loch Grannoch in Galloway the difference between mean and minimum ANC was in the range 22-107, with a mean of 59. The 7 Loch Ard sites showed differences in the range 18-49 with a mean of 25. The overall mean difference at both sites was 41. With the exception of three of the sites at Loch Ard where the difference between minimum and mean ANC was 18 all other sites had a difference greater than 20 μeql^{-1}. The argument for the difference between ANC minimum and mean being over 50 is exaggerated, the claim of a difference in the order of at least 20 μeql^{-1} is more reasonable.

and the difference between mean flow chemistry and high flow chemistry is much greater than 20".

The Fisheries Trust agreed that this tight sensitivity matched well with their experience of the impacts on salmon and trout "*from electrofishing in Galloway we normally have quite a tight band where you do find healthy salmon but it can literally be 100ms where a small burn comes in … the trout picture is so much more confusing there are issues to do with the salmon to do with access, habitat and all of that …trout are far more [resilient]*".

This agreement between the Forestry Commission Hydrologist and the GFT over the sensitivities of fish to changes in ANC, and the utility of generating local ANC response curves for salmon then led to a discussion of how this could be instigated in practice with the GFT asking the Forestry Commission "*how much of a big job would it be*". If it was to take place the Fisheries Trust were keen to ensure that the fish data were matched to ANC data from high flow samples. The Forestry Commission Hydrologist agreed to this recognising that "*the question in terms of the guidelines is: is selecting 0 for high flow sufficient to reflect that or not, it's worth checking that*".

He then refers to the literature to suggest possible alternative values "*the highest value being selected is 50*" whilst "*20 is probably a value that is recognised in a variety of countries as one to use*". He argues, referring again to the notion of *natural acidity* that a value of 50 "*has to be used very carefully because of … this issue of naturally acidic systems*" arguing that these systems "*would never reach [ANC] 50 and [that an ANC of] 20 is more appropriate*".

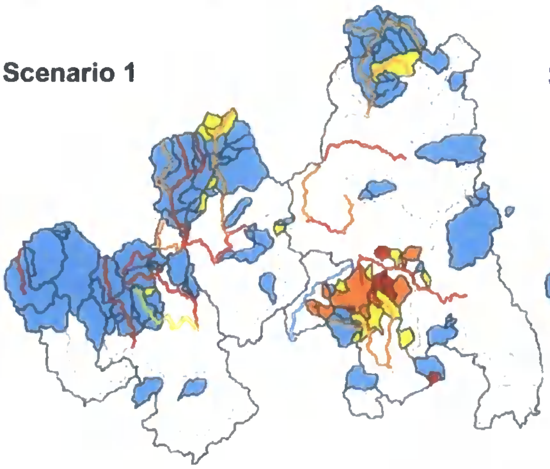
The local Galloway Forest District Manager summarised "*it seems to emerge from this that we could use existing data, some of the Galloway Fisheries Trust particularly to build on our understanding of these thresholds of recovery*" and it was minuted as an action point that the GFT and the Forestry Commission Hydrologist should work together to determine ANC-fish response curves for Galloway.

The discussion above has been detailed in some depth as it shows willingness on the part of the Forestry Commission at a policy level to integrate local data and knowledge. It is, however also important to note that this willingness is based around integrating ecological data *into the Critical Loads approach*; as such, it continues to reinforce the mechanism-down "forest effect" of the *Forest and Water Guidelines* and inherently suggests that the Critical Loads approach is a more appropriate tool for the identification of the "forest effect" than ecological data; there is no consideration of using ecological data by itself as an indication of impact. Furthermore the debate is constantly framed in terms of Science, with the academic literature used as a constant point of reference to enforce and support the Forestry Commission's decisions. It is also notable that, within this meeting, those with a view of a wider "forest effect" do not criticise use of a model *per se*. The Fisheries Trust, for example, are happy to integrate their data, even though they had not yet seen the implications of the model mapped in practice and stated in Chapter 4 that they were taking the Critical Loads approach on faith.

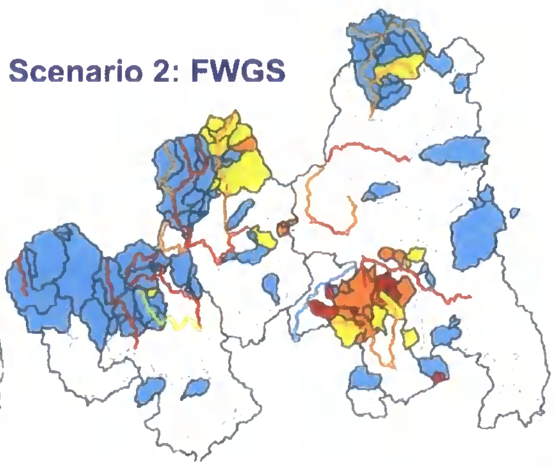
7.2.2b The Maps

Figure 7-5 Critical loads exceedance scenarios for the high-flow study sites. Note that areas not coloured are those for which critical loads exceedance data were not collected.

Scenario 1



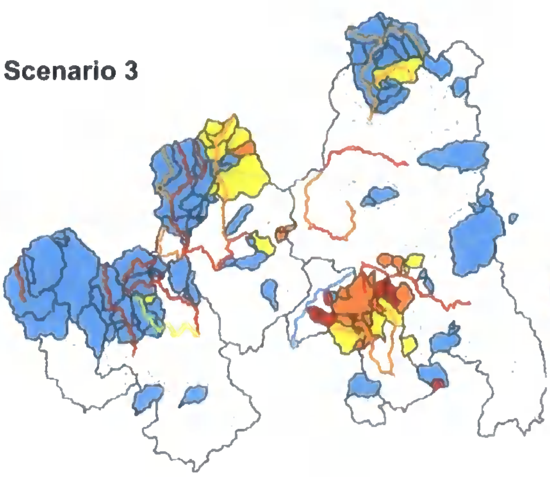
Scenario 2: FWGS



	Scenario		1	2	3	4
	ANC		0	0	20	20
	S_{DEP} Year		2004	1995	2004	1995
Exceedance >0.5 keq ha^{-1} yr^{-1}	Fail		8	10	15	20
Exceedance >0 keq ha^{-1} yr^{-1}	Marginal Fail		8	14	14	14
Exceedance <0 keq ha^{-1} yr^{-1}	Marginal Pass		17	15	13	13
Exceedance <-0.5 keq ha^{-1} yr^{-1}	Pass		82	76	73	68

Numbers are numbers of catchments in each class (of 115)

Scenario 3



Scenario 4

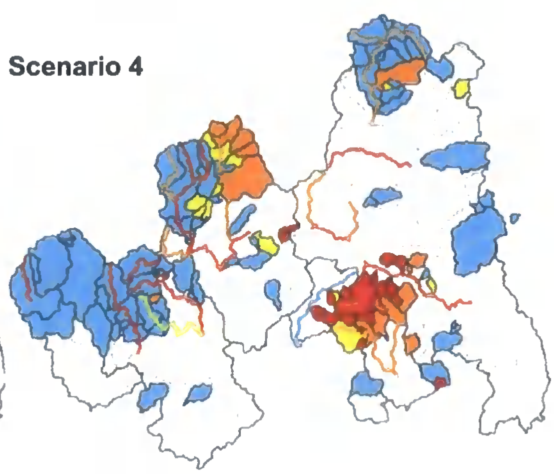
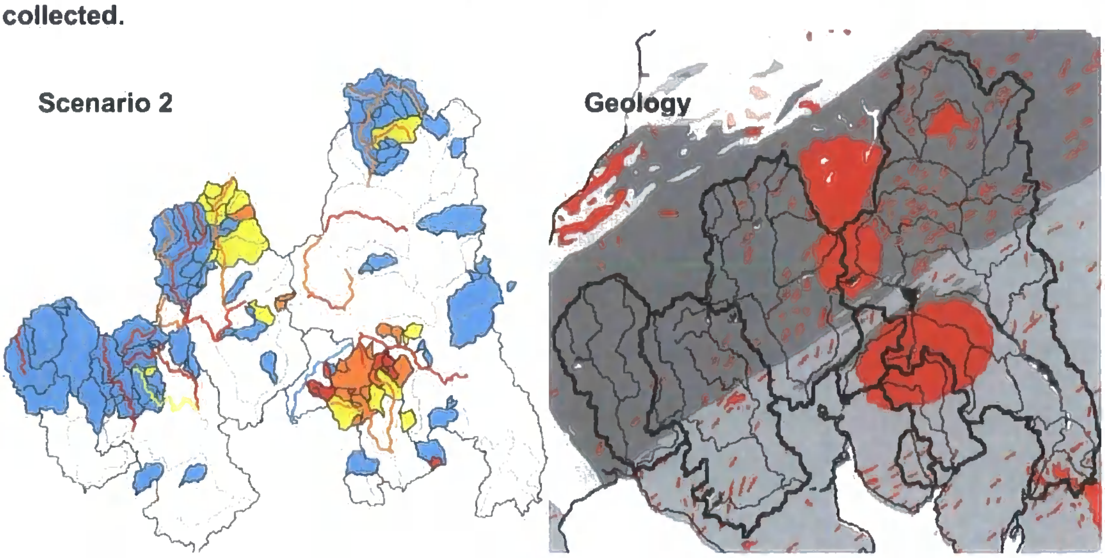


Figure 7-5 shows the Critical Loads exceedance scenarios generated in 6.6.2d; the first two scenarios use an ANC value of zero under both contemporary (2004) and historic (1995) total S deposition scenarios; scenario 2 follows the rules set down in the *Forest and Water Guidelines*. The second set of scenarios present the same data but with the ANC value modified to 20. The samples are all high flow samples in line with the *Forest and Water Guidelines*.

A comparison of the Critical Loads model with the wider "forest effect" put forward by the impact-up view of the "forest effect" shows little correlation. This is fact recognised by the Forestry Commission Hydrologist: "*there is clearly a mismatch between SEPA's initial classification and the Critical Loads exceedance sites*" (FCH). The problems in the Bladnoch, Cree and Luce highlighted in the fisheries data and SEPA ecology based classification are not matched by the Critical Loads approach. Instead, the Critical Loads exceedance results reflect what would be expected as a result of geological sensitivity with the areas at greatest risk being identified on the granitic plug at the north of the Fleet and the east of the Cree (Figure 7-6).

Figure 7-6 Critical Loads exceedance (scenario 2: FWGS) and geology. Note that areas not coloured on the critical loads exceedance map are areas for which data were not collected.



Exceedance >0.5	Fail	
Exceedance >0	Marginal Fail	
Exceedance <0	Marginal Pass	
Exceedance <-0.5	Pass	
Units: keq $ha^{-1}year^{-1}$		

Igneous	Most acid sensitive	
Silurian	Acid sensitive	
Ordovician	Least acid sensitive	
Other	Less acid sensitive	
Source: BGS 1:650,000 Bedrock geology		

Decreasing sulphur deposition from east to west (see Figure 6-18) will also play a role, as will proximity to the hills between the Cree and Dee which also increase deposition. Nonetheless it is relatively clear that even using 1995 deposition and an ANC of 20, very few sites are identified in the Luce or Bladnoch, and only the eastern Cree is identified as at risk, whilst these sites all suffer from impacted ecology. The reasons for this mismatch are discussed in relation to *natural acidity* in section 7.2.4.

7.2.2c Stakeholder Discussion

In terms of comparing the scenarios, the Forestry Commission Hydrologist noted that changing the scenarios didn't "*make a huge difference, I think it doubles the number of failed catchments; it's significant in terms of numbers but it doesn't mushroom cloud*". Fisheries also noted this and pointed out that "*[ANC 20] doesn't really particularly suddenly start to tie up with the biological data*". The Forestry Commission Hydrologist did not disagree stressing that "*It basically adds to the surrounding sites; which is in one sense good in terms of understanding the sensitivity it tends to reinforce the granitic areas as being most at risk and picking up a couple more sites in the Cree. It also strengthens the exceedance in existing sites*".

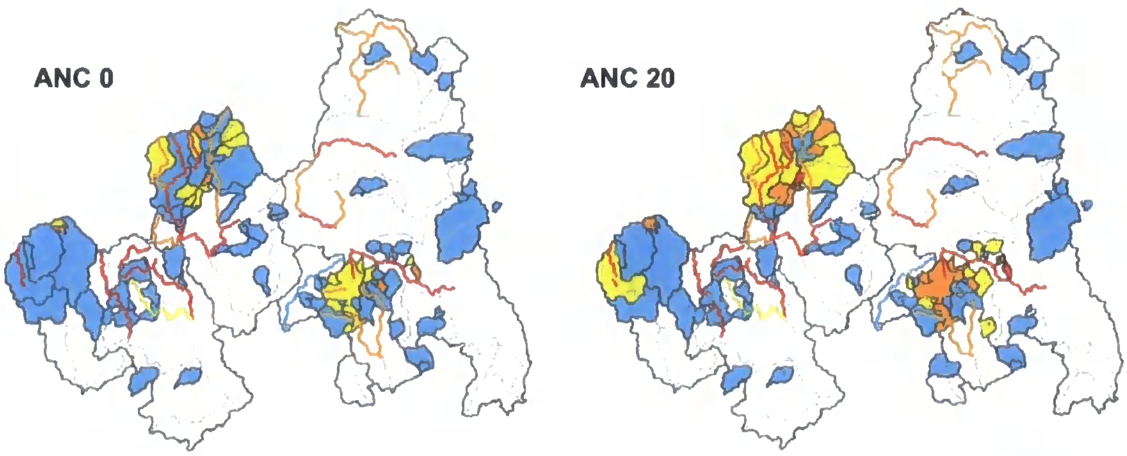
Nevertheless, in spite of this mismatch the Fisheries Trust remained keen to contribute their data to the generation of regional ANC curves in an attempt to regionally refine the Critical Loads model. The GFT were also keen to ensure that the buffer around zero (marginal pass/marginal fail) was taken into policy "*why not have these areas where the [approach to be taken] is to look at it in more detail. I agree the ones that have definitely passed then it would be silly for you to waste time*".

The Forestry Commission Hydrologist agreed with this, saying that in practice this is done informally and that they "*could formalise that process and say that 10%-20% of the Critical Loads and we'll repeat the process or within ±0.5. Just to check it's on the right side of the line*" he stressed that this was something that would be done informally when they check the calculations and that SEPA are contacted and that "*there is an opportunity for [SEPA] to come back and say 'no; it's a bit marginal – do it again*". This discussion concluded with an agreement to formalise a flexible boundary around Critical Loads model's pass/fail. It also included a reinforcement of the Forestry Commission argument of "natural acidity" (non-forest-exacerbated acidity) and the need for SEPA to make their classification more robust.

Again it is important to note that the Critical Loads exceedance scenarios do not suggest that altering the ANC limit will contribute to a better match with ecological areas of impact. It is not therefore likely that using the Critical Loads model will lead to the Forestry Commission changing their management practice in the lowland catchments seen as "at risk" by the impact-up "forest effect". The extent to which the use of the Critical Loads model as a means of guiding forest management is a factor that influences forestry policy and practice in addressing the "forest effect" depends on whether or not the "forest effect" is identifiable in these lowland catchments. Chapter 8 investigates this. Irrespective of the findings of Chapter 8, Fisheries Trust stakeholders believe that there are impacts in these catchments; therefore their willingness to contribute to a model that shows no signs of identifying the areas of concern to them shows the potential to be a factor that minimises their influence on the "forest effect".

It is recognised that the data presented at the meeting are simply from one single event; Figure 7-7 below shows that a similar geographical distribution of results were found using 1995 chemistry with very few exceedance (orange or red) in the Bladnoch, Cree or Luce and the igneous plug in the upper Fleet contributing the most sensitivity.

Figure 7-7 1995 Critical Loads Exceedance (Puhr, 1997) Note that areas not coloured on the critical loads exceedance map are areas for which data were not collected.



Exceedance >0.5 keq ha^{-1}year^{-1}	Fail	
Exceedance >0 keq ha^{-1}year^{1}	Marginal Fail	
Exceedance <0 keq ha^{-1}year^{1}	Marginal Pass	
Exceedance <-0.5 keq ha^{-1}year^{1}	Pass	

Whilst Figure 7-7 was not presented at the meeting, and is introduced here for context, it suggests that the Critical Loads method may have been showing consistent results through time. A larger number of regional datasets would be needed to better confirm this, however, the similarity of sites suggest that as a model designed to map the intersection between geological sensitivity and deposition inputs, the Critical Loads model is doing its job: the question is whether this is an appropriate approach for detecting the "forest effect".

7.2.3 The 300m rule

7.2.3a The Map

Figure 7-8 Closed canopy (>8m) forestry estimated from satellite imagery 2005 in relation to the 300m contour highlighting the areas in which the *Forest and Water Guidelines* need to be applied.

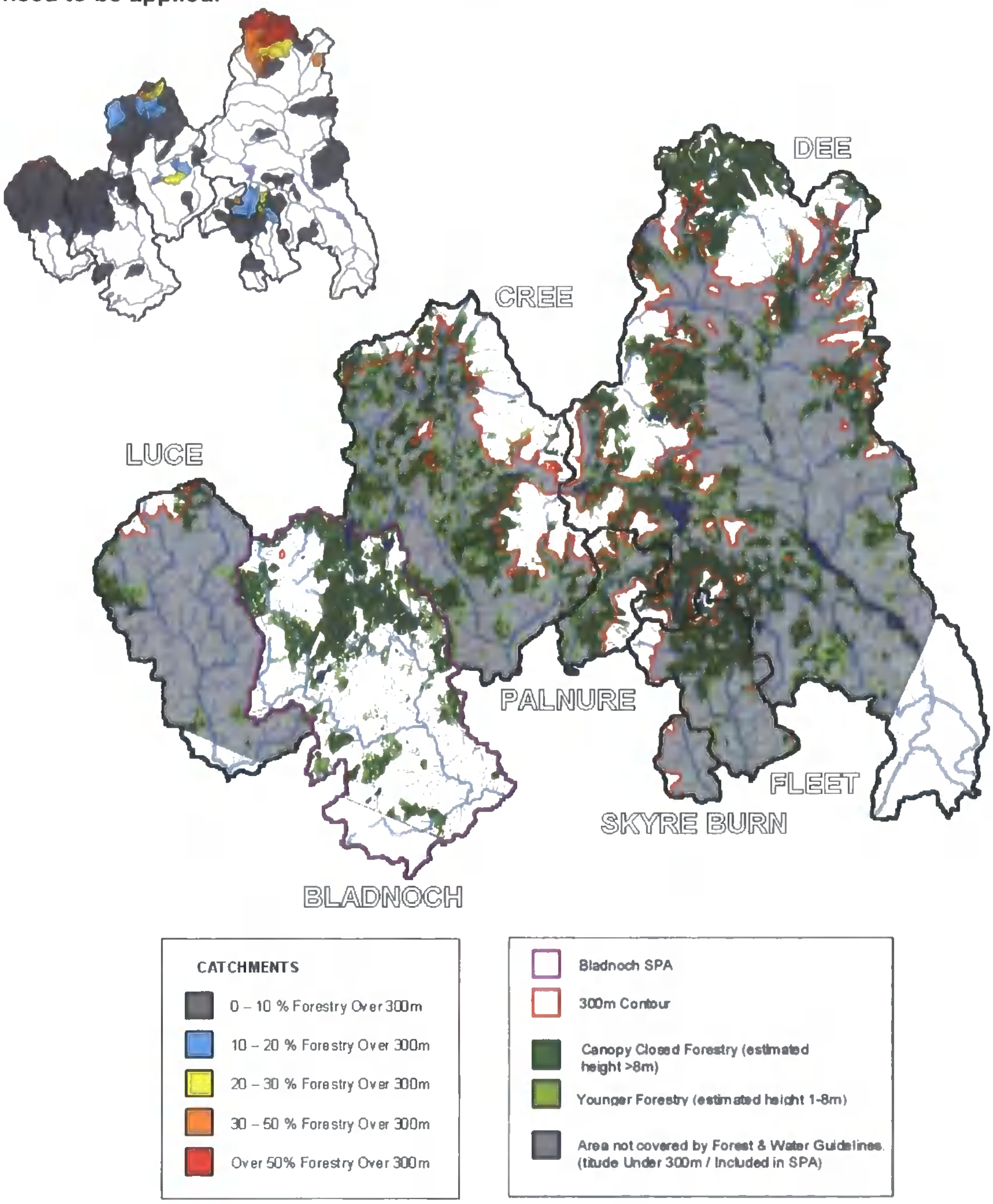


Figure 7-8 illustrates the areas in which the *Forest and Water Guidelines* apply (see 6.6.2d for the details of its creation). The Luce and Cree have very small proportions of forestry below 300m. It should be noted that the Bladnoch is only covered by the guidelines because of its SAC status; only a very small proportion (see contours on Figure 7-8) is over 300m. The inset map shows the proportion of forestry over 300m in each of the study catchments; only the Carsphairn block in the northern Dee is identified as having a large proportion.

7.2.3b Stakeholder Discussion

The 300m rule was introduced by the Galloway Fisheries Trust who stressed that it was one of their strongest concerns as they felt that "*the most impacted sites are all below this 300m rule*" They referred in particular to the Fleet and the high Cree and stressed that in most areas there were very few trees above 300m "*from our point of view the 300m rule, the trees nearly always seem to stop below it*" (GFT). The Galloway FC District manager largely reinforced this point "*we're largely not restocking above 300ms... some sites may be around for maybe the next 10 years but beyond that they'll disappear*" (FC-G).

The Galloway Fisheries Trust pointed out that the 300m rule was a barrier to the Critical Loads model being a useful tool and argued that "*you could play around with ANC or whatever and it still wouldn't make any difference*" as if the area was below 300m the Critical Loads approach would not be necessary (GFT).

The Forestry Commission Hydrologist drew on the science behind the scavenging approach (Fowler *et al.*, 1989) and argued that "*the models are fairly straightforward in terms of showing that deposition increases with altitude and the interaction with cloud is a strong one*" but stressed that its fundamental purpose was as a risk-based sifting approach "*at the end of the day [the 300m contour approach] was used as a way of focussing down on the areas of greatest risk*".

He defends the approach with four further arguments i) deposition conditions are improving ii) the approach taken in the guidelines includes precautionary measures such as using 1995 pollutant deposition and high-flow sample ANC of zero (see 7.2.2a(ii)) iii) the approach was a jointly badged document agreed with other agencies (see 4.3.1 for counterpoint) and iv) that the approach would require testing and refinement to determine whether or not it was effective in practice.

"*What I'm saying is that I think the process is robust at the moment in terms of focussing on the areas most at risk, we need to go forward and apply this, we need to see how it comes out in terms of [catchment-based assessment]...but we'll have to see how the scheme applies, we'll also see in below 300m SAC catchments*"

He does however make it clear that if, once the assessment has been applied and shown to be insufficient then the guidance will be updated "*there is no question that if the assessments that we subsequently do show that the 300m contour is not sufficient in terms of ruling out acidification then it will be brought down*" in addition he stresses that the approach will need to be "*linked into SEPA's classification exercise ... depending on what system is used for that classification exercise*".

The origins of the 300m rule were questioned by a local SEPA representative (SEPA-1) arguing that the cloud base locally may be below 300m on occasions and questioning the justification of the use of aviation data in areas quite remote from forested areas. The Forestry Commission Hydrologist defended this as it was "*the only dataset available*" and agreed that "*more local datasets looking at duration and altitude*" would be useful, agreeing with the local SPEA representative that "*you need to take in other geographical factors as well*" (FCH).

The Fisheries Trust questioned whether the approach was ever tested in advance before it was instigated arguing "*its like all the SEPA areas that we would agree on the whole fish data suggests – it just misses it. Did you print off maps? Did everyone understand ... because the SEPA rep who sat in that group (SEPA-G), I can remember in a Cree board meeting [him] saying that the Guidelines would have a huge impact on the high Cree, and it was minuted and I don't understand what got changed after that...*".

The Forestry Commission Hydrologist justified the decisions in the *Forest and Water Guidelines* by saying that they followed "*an objective point of view*" resulting from "*applying the science*". He confesses that "*no, we didn't look at the implications. We were to apply best science to say: 'if we wanted to focus on areas at greatest risk then this is one way of doing [it]' so no, we didn't consider how that would pan-out.*". He argues that the approach does work and that there are large areas of Scotland picked up by the method, and so requiring assessment. He stresses a risk based approach is necessary as "*if we said we'll do it across the whole board regardless potentially that a huge task in terms of all of work that would have to be done.*" He argues therefore that from "*a practical point of view, a cost-effective point of view, and a scientific point of view*" a risk based assessment is the best approach and that "*high altitude crops are at greatest risk*".

In this way we can again (Cf. 3.1.2) that by following the "objective" view based on science is driven by subjective, pragmatic concerns so as to minimise the "huge task" of applying the guidelines to all forest activities in addition to scientific ones. This is, again, understandable from an organisational viewpoint, the question is: do the Forestry Commission, in selecting their risk-based approach, target the areas at greatest risk from the "forest effect"? The impact-up "forest effect" argues that they do not, that areas below 300m are highlighted by both SEPA and Fisheries datasets as concerns. However this begs the question: are these areas suffering from a "forest effect", and, if not, what is the cause of the ecological problems in these areas? The following section discusses the debate of wider "forest effect" vs. natural acidity.

7.2.4 Non-Forest Acidity

7.2.4a What causes impacts if the critical load is not exceeded?

The issue of non-forest exacerbated acidity, acidity that would exist in the current deposition climate irrespective of a "forest effect", is raised by the Forestry Commission Hydrologist as an answer to the mismatch between the areas identified as impacted by the SEPA characterisation and the Fisheries Trust data and those identified as at risk by the Critical Loads model. Referring to non-forest exacerbated acidity as "natural acidity" the FCH argues:

"there is this issue of assessing "at risk" just on the basis of assessing acid sensitivity – you can have a naturally acid sensitive water body, that won't be at risk from anthropogenic acid deposition and because deposition levels are low but will still be impacted by acidity because of natural acidity but that's essentially natural acidity and the only way you'll be able to turn that around is effectively to lime the system, which wouldn't be sustainable. If you just use a characterisation exercise like soil sensitivity, geological sensitivity or invertebrate fauna potentially that is just showing sensitivity in terms of acidity; but that doesn't tell you if these systems are actually being acidified due to anthropogenic influences or forestry from that point of view."

The Forestry Commission Hydrologist's argument is, therefore, that as the Critical Loads model takes deposition and geological sensitivity into consideration it better represents the areas at risk from scavenging, the agreed "forest effect" than fisheries or ecology data. These datasets are shown as only indications of acid impact; not scavenging impact. Impacts identified in catchments outside of the Critical Loads exceedance areas are therefore naturally acid sites, not sites in which the scavenging effect has contributed to acidity. Any change in forest management would not be improving them, and liming would increase their pH beyond their natural status.

The Fisheries Trust argued against the view of a return to non-forest exacerbated acidity saying "*most of these acidified areas you're talking about here a short time ago supported fish... all of these red areas were known to support dense populations of migratory fish, trout and I'm sure at the very tops of these rivers, you're right I mean you cant go right up it'd be unnatural, but it'd be a relatively small area of natural acidity*" (GFT). The Forestry Commission's response to this was to argue that this needed proving and "*in order to achieve that there is a need to look at historic fish data and historic invertebrate data*".

With regard to a validation of argument of the return to non-forest exacerbated conditions, the views of GFT-S, a long-term Galloway resident in Chapter 5, support the GFT's argument in claiming that the Bladnoch, Fleet and Cree all had healthy fish populations were illustrated. The GFT report of 1989 also canvassed local opinion and determined similar results: furthermore, the GFT monitored the decline of the fish population in the Bladnoch (SEPA-G; GFT Report, 1993). In dismissing anecdotal evidence such as this and demanding scientific proof it is possible that the Forestry Commission are preventing themselves from accessing local knowledge that would help them better manage the environment. Quantitative data regarding non-forest-exacerbated acidity are also available, and Figure 9-2 suggests that long-term pH, certainly for the Cree, has yet to return to its pre-acidification pH: further research is needed to determine this more conclusively one way or the other.

7.2.4b Joined-Up approaches

The clear difference in approach between SEPA and the Forestry Commission approaches to identifying and managing the "forest effect" were apparent to all. The GFT suggested that SEPA's water body characterisation should be used as their base for the *Forest and Water Guidelines* risk-based approach in the place of the 300m rule.

In response, the Forestry Commission Hydrologist admitted that the FC and SEPA had yet to "*have a discussion about how our guidelines and the WFD come together*" and how the FC and the *Forest and Water Guidelines* "*interrelate with whatever approach SEPA finally adopt for the purposes of the WFD*" but recognised that there had to be some "*tie up*" put in place. As a means to do this the Forestry Commission Hydrologist urged SEPA to avoid following a qualitative approach to characterisation similar to that followed by the EA in England and Wales and stressing instead a quantitative "*Critical Loads*" based approach would be better. The Forestry Commission Hydrologist stressed the importance that typologies used by SEPA to define areas of good and high status with regard to acidification took naturally acidic streams into consideration.

The argument being that if a typology based on a system from a non-acidified system was used, the targets set would be unattainable.

"*we need to be sure that the biological community you're using to classify your good and high status [is of] a typology that represents naturally acidic systems so that when you go into that system you're not trying to apply a wrong endpoint in terms of good status … and that comes down to typology and how many typologies you will have, and whether you have a naturally acidic typology class of sites – because otherwise you're setting an objective that is not obtainable*" (FCH)

I then reiterated the Fisheries Trust's argument asking whether if the Forestry Commission and SEPA came to an agreement over the approach used to classify water bodies whether they would consider using the WFD rivers classified as at risk in place of the 300m rule. The Forestry Commission Hydrologist remained reluctant arguing that "*just having forestry in that catchment may not necessarily be adding to that acid impaction because it depends on how much additional deposition that forest is capturing and how that additional deposition compares with the overall deposition at the site. You could still have a system that is classified as still at risk still diminished in biological terms but it could be that we've now got the emissions reductions sufficient to reduce the deposition below the critical load and that the added scavenging or impact of forestry is neither here or there so that we're in a recovery phase, but ok it hasn't quite recovered there due to a lag and therefore its inappropriate to constrain forestry if its not going to materially affect that outcome*".

The Forestry Commission Hydrologist however acknowledged that they "*need to come together*" and expressed hopes that SEPA might come around to following the Critical Loads approach saying that it would make the challenge "*simpler*" but recognising that "*at the end of the day its still got to be married up with the biology*" and that the Forestry Commission are "*required to do so because … water bodies that are classified as at risk under the Water Framework Directive will need a programme of measures and if forestry is marked out as an activity that contributes to a pressure then we're going to be required to show that we're tackling that contribution*". He stresses that the current approach to this would be to apply the *Forest and Water Guidelines* but agrees that "*if they're shown by trial and error that they're insufficient and need amending then well yeah I mean there is an expectation that we'll review the guidelines again in due course hopefully learning from the last 5 to 10 years of experience*". He stresses however that it is still "*relatively early days*" and that the approach needs to be applied and draw from experience in sites such as the Bladnoch, Loch Dee and Wales.

The conclusion of this debate was with an action point for SEPA Ecologist and the Forestry Commission Hydrologist should "*work more closely regarding these issues*". It is however clear from the focus of the debate that there is an expectation that SEPA's classification should become more "*robust*" (FCH), and so better represent the mechanism-down view of the "forest effect" represented in the guidelines rather than that the Forestry Commission should change their approach to adapt to the impact-up view currently presented in SEPA's WFD classification. The driving force behind this argument is the insistence that the "forest effect" is well understood and that the Critical Loads approach and the 300m rule objectively represent in practice; the following chapter tests these assumptions.

The extent to which this insistence on the mechanism-down approach is a factor affecting best available knowledge being included in forestry policy and practice depends to some extent on the nature of the "forest effect" itself. If there is indeed a return to non-forest exacerbated acidity in these areas then the *Forest and Water Guidelines* approach is working: the "forest effect" is over and no changes in management will help these naturally acid areas recover. The following chapters use the Catchment-based database generated in Chapter 6 to statistically explore the extent to which this is the case and to provide further insight into whether a "forest effect" can be identified in areas below 300m where the Critical Loads approach is being interpreted to say forestry has no impact.

7.2.5 "Beyond the guidelines"

In response to the debate over the 300m rule the Fisheries Trust took the opportunity to explore the extent to which the Forestry Commission was capable of going beyond the guidelines. They drew on experiences with the local FC conservator, who in determining his approach to private forestry "*answered most of the criticisms [the GFT] levelled by saying 'I'm going through the process as outlined, I have no choice when it comes to private [forestry]'*" and took the opportunity to ask the policy maker "*is that the sort of way the guidelines are seen as, are the latest versions what someone like [the local FC conservator] is meant to just stick to?*" (GFT)

The Forestry Commission Hydrologist's reply was "*well, they're guidelines; they're best practice we're applying nationally to deal with these issues, so that's the first place you go to set out a methodology*" flexibility is however perfectly acceptable "*there is no harm in looking at the more underlying detail and if that shows that there is change needed that can be implemented*" (FCH).

The Fisheries Trust then pressed to determine to what extent it was possible to go beyond the guidelines asking firstly whether a) if biological data could be used in place of Critical Loads exceedances and b) if Critical Loads tests could be applied below 300ms.

The local Forestry Commission conservator's answered that the Critical Loads results would have to be followed but that they would be happy to perform tests in areas below 300ms if it was raised as an issue during the forest plan consultation. "*the difficulty is there is a differentiation between doing that assessment [below 300m and] so in the Fleet Its likely we would say 'yes ok we'll do some Critical Loads work here', ... but likewise where we do go down that route I have to accept what [the Critical Loads approach] tells me at that point of time in terms of the decision to be made*" (FC Conservator: FC-C)

It was then argued that if ecological data showed an impact in the area and the critical load showed it to be fine that there was no way for the *Forest and Water Guidelines* to deal with that.

The local FC conservator argued that what would be needed was to "*coalesce the two methodologies so that those sorts of anomalies don't arise significantly*". The Forestry Commission Hydrologist reiterated that the best method to do this was by modifying the ANC value. He stresses that for this to happen some quantitative research would be needed "*it shouldn't just be on the back of a whim, we need to have some evidence base to say, we've applied it to salmon or whatever in this area and so we need 20 – fine*". He also stresses the need to remain focussed on areas where forestry is having an impact, again stressing that "*Biology of its own wont be enough to identify the cause of the impact, and we do need to bear in mind the natural [non-forest exacerbated] acidity issue to make sure that what you're trying to achieve is relevant for those particular areas*".

As a result of the discussion the local Forestry Commission conservator agreed to apply the Critical Loads approach below 300m where it is matched by local concerns. It is however stressed that the result of the Critical Loads model will be followed even if ecological data shows an impact.

This, whilst a step towards including local concerns in the forest management process, is still based in the assumption that the Critical Loads model is a sufficient test for the "forest effect". If the local stakeholders who believe that there is a forest impact in the Bladnoch, Cree and Luce below 300m are right; then the findings presented in section 7.2.2 suggest that all decisions based on the Critical Loads model will be of little use in terms of assisting management; and as such the use of the Critical Loads model will be a factor preventing best available knowledge being applied in both forest policy and practice; chapter 8 explores this issue.

7.3 Changes 2004-2007

7.3.1 Reinforcing the local

One of the most significant changes that has taken place during the course of the project is a reinforcement of the relationships between local stakeholders, which begin to lead to changes in management practice. The GFT report of 2006 attributes change in the attitude of the local FCS conservator's approach to forest management as a result of the stakeholder meeting "*Since [the meeting], the local FCS conservator approached both SEPA and GFT to outline a number of actions that he wished to progress. These include research on whether the present CLA is robust enough for Galloway (particularly the ANC figure used) the use of relevant biological data in informing the assessment of schemes and to continue water sampling (for CLA) in areas believed to be at risk, including under 300m in altitude. He has recently worked with forestry interests to significantly rewrite a forest plan in the headwaters of the Bladnoch which will assist in addressing some acidification concerns. It is hoped similar commitment is made by FCS on any replanting of other sensitive areas*" (Galloway Fisheries Trust, 2006). These significant changes include large areas of open space and buffer strips up to 100m in length (GFT, *pers comm.*). In doing so we see the Forestry Commission accepting changes in forest management put in place that, whilst following the *Forest and Water Guidelines* in terms of applying to a Special Protection Areas, go beyond them by accepting the use of relevant biological data for decision making and questioning the Critical Loads approach. In doing so the approach taken by the local FCS conservator moves away from the mechanism-based view of the "forest effect" driven by the *Forest and Water Guidelines* to the more impact-driven approach.

Similar changes are seen within SEPA. In correspondence with the Forestry Commission related to new design plans in both the Bladnoch and Dee systems SEPA argue that "*given the changes in environmental legislation*" there is need for a "*fresh look*" at design plans, even those in areas previously agreed (SEPA, 2006a, b). SEPA argue drawing on the Water Framework Directive, the Scottish Forestry Strategy and the Scottish Biodiversity strategy that "*while the Forest and Water Guidelines 4th* *edition is a very useful starting point ... statutory and non statutory bodies involved in sensitive catchments are now required to go beyond FWG especially in sensitive when assessing water quality and habitat issues*" (SEPA, 2006a).

Correspondence following the meeting indicates that both SEPA and the FC conservator found the meeting "*very productive*". SEPA acknowledge that *"the 4th edition of the* Forest and Water Guidelines *is, and should remain, the document of reference for practitioners and regulators of forestry activities."* They however do not preclude deviation from them "*where robust data exists to indicate that a CLA assessment on its own does not go far enough to offer the degree of confidence required to approve forestry schemes".*

In response to comments from the Forestry Commission regarding the success and failure of Critical Loads sampling SEPA argue that they "*would prefer to see CLA output used in conjunction with invertebrate analysis and fish survey data, in particular egg box studies*" arguing that "*this triad of output, discussed with the relevant parties via focussed workshops, would add greater understanding to what is a complex issue*" (SEPA, 2006b). This is a great step towards what the Social Learning approach would advocate as the best approach to environmental management.

In addition, there is also evidence of improved working relationships between SEPA and the Fisheries Trust, seen in the argument for the inclusion of fisheries data within the "*triad of output*" above, and more explicitly within the comments regarding the design plan in the Dee: "*SEPA would be more reassured on accepting the plan proposal if further fisheries work was done within the forest plan area. The Galloway Fisheries Trust has no data [on the burns in question] but survey data downstream suggests that it is one of the most important spawning tributaries on the Dee. Further survey work ... should be completed to ascertain the health of fish populations and whether the plan requires revising.*" Furthermore they stress the importance of including information from the Galloway Fisheries Trust "*I also feel the benefits of good working relationships between ourselves and the Galloway Fisheries Trust will enable future decisions to be made using the best available information.*"

The strengthening of local relationships and the (new-found) enthusiasm of SEPA to develop relationships with other sources of knowledge, such as the Fisheries Trust, and to determine best approaches to management in workshops with other interested parties is a positive development in Galloway in terms of a Social Learning approach. However if the Forestry Commission Hydrologist is correct and the poor water quality that is being seen in the Luce, Bladnoch and Cree is not a result of a "forest effect" but indicates a return to non-forest exacerbated acidity then these changes in management will be costly and ultimately ineffective in terms of mitigating the problems; the following chapters focus on a statistical evaluation of the "forest effect" to attempt to provide additional information to help determine which "forest effect" is really happening.

7.4 Discussion

7.4.1 Methodological approach

The main aim of this chapter was: *to explore the extent to which inter-stakeholder discussions of mapped "forest effects" influence the inclusion or exclusion of knowledge in forestry policy and practice.* To do this a methodology was created that combined map-based discussions, commonly found in the literature surrounding Participatory GIS (PGIS; Dunn, 2007) and stakeholder-analysis (Prell *et al.*, 2007) with Participant Observation (Cook and Crang, 2007) and Network Theory (Bulkeley, 2000).

In this chapter stakeholder discussions of map-based data (commonly used in participatory GIS) were used as a means to assist the inclusion of local knowledge in the decision making process by allowing it to be discussed alongside the knowledge more usually given privilege in decision making (Dunn, 2007). This was done by mapping fisheries data and presenting it for discussion alongside the maps of the areas targeted by the policies of both the Forestry Commission and SEPA (based on FC, 2003 and SEPA, 2007 respectively). In doing so fisheries data, and the wider "forest effect" that it supported could be discussed in relation to the policy designed to manage the "forest effect". This map-based discussion approach was appropriate for this task and has a significant history within other studies particularly in the participatory GIS literatures surrounding natural resource planning (Ventura *et al.*, 2002; Walker *et al.*, 2002) and environmental management and conservation (Sieber, 2002; Tulloch, 2002). For this project, the interview analyses were used to determine the layers of the GIS most important to present. It was clear from the interviews that local stakeholders required maps of how Critical Loads Exceedances were spatially distributed (Section 4.3.1b), particularly in relation to the 300m rule (Section 4.3.2) so as to be able to understand the implications of the 4th edition of the *Forest and Water Guidelines*. It is particularly notable that this was also the first time that the *Forest and Water Guidelines* approach of catchment-based Critical Loads had been presented, particularly for Galloway, but also at a large scale; the previous experiment being Nisbet *et al.* (1995) which simply used the Loch Dee sites. Other studies of Critical Loads exceedance at a regional scale exist (Bridcut *et al.*, 2004; Aherne and Farrell, 2002), but are not focused within the Galloway region. For the purposes of stakeholders within this study, it was clear from the interviews performed that it was the lack of *local* maps that was the greatest concern. Without these stakeholders found it difficult to visualise the impacts of the new *Forest and Water Guidelines*. It was for this reason that local maps of critical loads exceedance were expected to best stimulate discussion.

In terms of the influence of stakeholder selection, this study encourages the inclusion of the views of both those managing a resource and those dependant on that resource. In doing so it addresses concerns raised by many other authors that this inclusion is not commonly the case (Dougill *et al.*, 2006; Lane *et al.*, 2006; Ison *et al.*, 2007). Within the stakeholder group of this study, this was achieved by including not only the scientists involved in both FC and SEPA policies (FCH, SEPA-Ec) but the local land/environment managers (FC-G, SEPA-G) as well as impacted stakeholders with no official capacity with regard to implementation of policy (GFT). As discussed in section 2.3.3 these stakeholders represent the key viewpoints surrounding the "forest effect" and how it should be managed in Galloway. All those present, including those external to the region (FCH, SEPA-Ec) were familiar with Galloway and so were not disadvantaged by lack of local knowledge.

It is also important to consider the impact of inter-stakeholder relationships on the discussion and outcome of meetings such as these (Crang and Cook, 2007). The meeting was deliberately organised to reflect the style of a meeting that would normally take place between these stakeholders. The meeting was, for the participants, a business meeting. Whilst it is impossible to know the extent to which factors such as inter-personal relationships, the format of the meeting and any other external factors may have impacted the various stakeholders on the day in question (discussed in 7.1) the fact that the views discussed matched the results of interview analysis and participant observation strongly suggest that the format was appropriate.

7.4.2 The meeting as participant observation

As mentioned above the meeting was not solely an exercise in stakeholder-based participatory GIS, but more importantly an opportunity for participant observation. The participatory methods were designed to give the stakeholders the tools to argue their cases, the participant observation aimed to determine how these arguments were made, and explore the extent to which inter-stakeholder discussions of mapped "forest effects" influence the inclusion or exclusion of knowledge in forestry policy and practice. It is this combination of a PGIS/stakeholder-based approach (Ventura *et al.*, 2002; Dunn, 2007) with participant observation (Cook and Crang, 2007) and network analysis (Hajer, 1995; Jordan and Greenway, 1998; Sabatier, 1998; Bulkeley, 2000) that makes the approach in this chapter different from many other studies. By identifying how the knowledges held by the stakeholders who, in practice, have the responsibility to manage the environment it was possible to study the role played by the scientific discourse as a means to reinforce the mechanism based "forest effect" whilst marginalising any discussion of a wider "forest effect".

This is most clearly shown in discussions around the analysis of the Critical Loads approach. The maps presented (Figure 7-5) showed clear mismatches between the critical loads exceedances and the areas of concern for those who believe in a wider "forest effect", the areas identified as ecological risks by both fisheries data and the WFD characterisation data of SEPA. Two alternatives were suggested at the meeting i) that there is a wider "forest effect" in the areas identified as at ecological risk and ii) that these areas are acid, but that any acidity is not a result of the "forest effect". The arguments of the Forestry Commission hydrologist, in support of a return to non-forest-exacerbated acidity and argued with reference to recognised science of the forest sulphate-scavenging effect, were far more effective in terms of determining the action points from the meeting. Despite the fact that the model had been demonstrated as an ineffective method to identify risks in the areas in which the GFT had concerns, even with a critical ANC limit of 20, the GFT agreed to contribute their data to help refine the critical loads model. Similarly SEPA were encouraged to make their approach more robust, and it was suggested that they too should follow a critical loads approach. There was notably no suggestion that the local knowledge exhibited in the meeting should be used to set hypotheses for more detailed scientific research within the lowland catchments to identify if there was a "forest effect". Nor was there any discussion of alternative "forest effects" that might be playing a role in those areas such as base cation uptake (Miller, 1981), soil drying (Neal *et al.*, 1986), or sea salt scavenging (Larssen and Holme, 2006). Furthermore, there was little consideration of any intention to follow a precautionary approach even in the light of scientifically collected datasets that contrast to accepted and agreed knowledge of the "forest effect". Instead, forest areas outside the *Forest and Water Guidelines* were argued to be at similar levels of acidification to those in non-forest sites; a return to non-forest exacerbated conditions. Whilst this may be the case, and the ecological effects may or may not be driven by forestry, and they may or may not be a delay of response between chemical and ecological recovery (Monteith *et al.*, 2001; Monteith and Shilland, 2007) this is not *known*. As such, it cannot be said for certain that there is no "forest effect" in these areas; a factor that should surely be at least considered given the ecological impacts, the WFD and the level of local concerns. The following chapter tests statistically whether or not a "forest effect" can be identified.

This privileged position of scientific arguments over local knowledge is expected under the social constructivist critique. Similar to Wynne's (1992) Cumbrian sheep farmers (Section 2.2.1c), the stakeholders shown in Section 4.3.3 to draw on local knowledge in support of a belief in a wider "forest effect" are swayed to follow the mechanism-down based arguments put forward by the Forestry Commission without strongly arguing their own knowledge (and data) that exists in contrast (Wynne, 1992). In terms of the discourse coalition approach of Hajer (1995) we see the science-based "mechanism-down" discourse gaining power by forcing the proponents of the "wider forest effect" discourse to argue in their terms. By focussing the debate on refining the critical loads model local knowledge stakeholders agree to offer support to a model that has been shown not to identify the areas where their concerns lie. Hajer (1995) identified similar findings with proponents of precautionary approaches during the debate over the installation of Flue Gas Desulphurisation technologies in power stations. In his case-study of the Chequers meeting in 1984 proponents of precautionary approaches were faced with a "discursive dilemma": *"either they could argue their case within the prescribed confines of scientific discourse or they could try to contextualise this discourse, question the numinous legitimacy of science and explicitly bring in policy choices".* In Hajer's (1995) study the supporters of a precautionary approach made arguments in scientific discourse and were easily quashed by better prepared CEGB representatives who argued that "*the UK was probably guilty of killing fish in Scandinavia, but that the evidence was not conclusive*" and that research was underway. This left the Prime Minister concluding the meeting by saying that "*she now knew there was no firm evidence and that therefore the critics should stop harassing the government*" (Hajer, 1995). The case of the fisheries is similar, by entering into a discussion for the refinement of the critical loads model, rather than arguing for an investigation of the wider "forest effect" the GFT lost an opportunity to encourage research that might identify the cause of their problems.

It is, at this stage, worth reflecting on the influence that additional external stakeholders might have had on the findings of this meeting, particularly the impacts of the presence of additional scientists with different policy network ties, levels of influence, political commitments and advisory roles, such as from the AWMN (Davies *et al.*, 2005), the Freshwater Fisheries Laboratory (Harriman *et al.* 2003) or from academic institutions (Puhr *et al.*, 2000). It is, of course, impossible to know how such a presence would have influenced the nature of the meeting, and the extent to which the discussions would have been driven towards greater deliberation of the mechanisms driving the "forest effect". If a greater discussion of mechanisms had occurred this may, in turn, have driven towards a consideration of further investigations to explore whether or not a "forest effect" could be identified in the areas below 300m. The fact that this meeting did not follow this path is important in itself as a reflection of the way that the science discourse is used in practice by the stakeholders who manage the "forest effect" in reality.

7.5 Conclusion

It is important to stress that in the absence of the data of Chapters 8 and 9 it is unclear as to whether or not a wider "forest effect" exists. If currently accepted science is to be believed then the impact-up "forest effect" may well be that expected under current deposition conditions irrespective of forestry; however if there is a "forest effect" below 300m or where the Critical Loads model passed then the mechanism-down "forest effect" may underestimate and misrepresent the problems. What is clear is the fact that alternative mechanisms may exist (Miller, 1981; Neal *et al.*, 1986; DoE and FC, 1990; Larssen and Holme, 2006) and that they are not being investigated. The following chapters focus on a statistical analysis of catchment-based database to identify which "forest effect" is better supported by an analysis of the best available scientific data.

Chapter 8 : A wider "forest effect"?

8.1 Introduction

8.1.1 Context: contested "forest effects"

Chapter 4 introduced the two different conceptions of the "forest effect" held by stakeholders. The mechanism-down "forest effect", recognised by Forestry Commission policy makers and represented in the *Forest and Water Guidelines,* is based on the scavenging mechanism of Fowler (1989) and represented in policy by the 300m rule and the Critical Loads approach. Local stakeholders, however, believe that there is a wider "forest effect" in lowland areas below 300m where Chapter 7 showed that the Critical Loads model suggests no risk of critical load exceedance.

This chapter draws on the catchment-based database created in Chapter 6 as a means of statistically exploring relationships between the proportion of forestry within a catchment and water quality variables. The aim of this chapter is to determine first if there is it is possible to detect a "forest effect" despite the 70% decline in sulphur deposition (NEGTAP, 2001). Following this, the chapter then explores whether the wider "forest effect" of local stakeholders can be identified by performing statistical analyses in areas that that the mechanism-down "forest effect" of the *Forest and Water Guidelines* does not identify as at risk.

8.2 Methods

8.2.1 Data availability and preparation

8.2.1a Data Availability

Table 8-1 shows the data available within the catchment-based database created in section 6.6.1. There are 13229 records available; however, the number of these that are available for statistical analysis was dependant on whether there was available forestry data linked to that data. Satellite-based forest height maps are available for 5 years of data (1989, 1995, 2001, 2003 and 2005). For the single-date high-flow surveys (section 6.2.1) data were joined to the nearest year: for Puhr 1995 and Durham 2005 this join was made to imagery from the same year; the Durham 2006 survey was joined to 2005 forestry. In doing so it is assumed that changes in forestry between these 2005 and 2006 will not have a significant impact on the relationships. In terms of the SEPA long-term data (section 6.2.2) only data from the years with forestry data were included; five separate water quality datasets were created. In total eight separate water quality survey datasets (see 6.2) were involved in the analysis that follows; the processing of these is discussed in section 8.3.4. Catchment data were available for all sites in all years: its processing is discussed in section 8.3.3.

Table 8-1 Data Availability

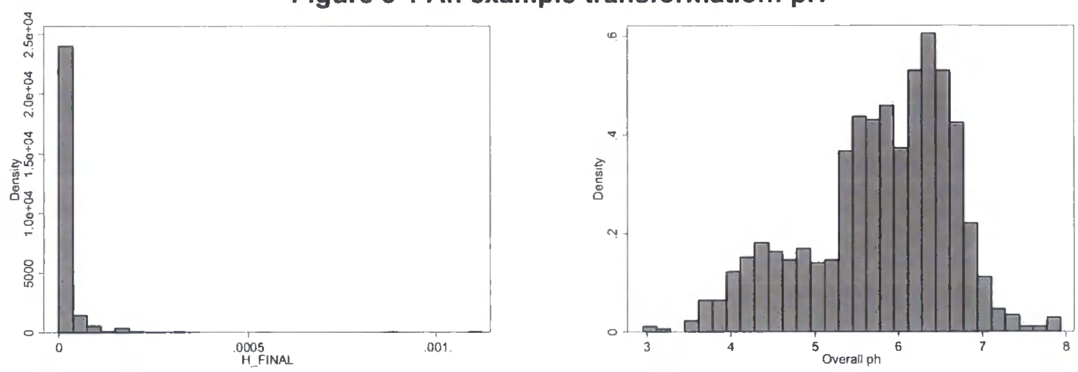
Dataset								
SEPA 1989	SEPA 1995	Puhr 1995	SEPA 2001	SEPA 2003	SEPA 2005	UoD 05/06	Variable	Variable name
Chemistry Variables (Number of available points)								
24	30	93	36	43	40	114	pH (units)	pH
16	27	93	34	43	36	114	Chloride (μeql^{-1})	Cl
16	26	93				114	Sulphate (μeql^{-1})	so4
						114	Nitrate (nitrogen component of) (μeql^{-1})	no3n
				3	27	114	Dissolved organic carbon (mgl^{-1})	Doc
6	7	93	11	20	31	114	Calcium (μeql^{-1})	Ca
6	7	93	11	21	31	114	Magnesium (μeql^{-1})	Mg
16	27	93	11	21	31	114	Sodium (μeql^{-1})	Na
15	26	93	11	21	30	114	Potassium (μeql^{-1})	K
16	26	93				114	Sea salt corrected sulphate (μeql^{-1})	xso4
6	7	93				114	Charge Balance ANC (μeql^{-1})	anc_cb
6	7	93				114	Critical Load Exceedance (μeql^{-1})	CLoadX
Forestry Variables								
EXCLUDED (see 8.3.2)							Average Puhr SWAIH index	SWAIH
✓*	✓*	✓*	✓*	✓*	✓*	✓*	% of catchment under forestry 2-8m tall	CC1 (*as TF)
✓	✓	✓	✓	✓	✓	✓	% of catchment under forestry over 8m tall	CC2
EXCLUDED (see 8.3.2)							% catchment under forestry 2-8m tall over 300m	CC1_o300
							% catchment under forestry > 8m tall over 300m	CC2_o300
Total S Variables								
✓	✓	✓	✓	✓	✓	✓	1995-7 mean total S deposition (keq $ha^{-1}y^{-1}$)	S1995
EXCLUDED (see 6.5.4)							2001-3 mean total S deposition (keq $ha^{-1}y^{-1}$)	S2001
Geology variables								
✓	✓	✓	✓	✓	✓	✓	Proportion of catchment on Igneous rocks (%)	Ign
✓	✓	✓	✓	✓	✓	✓	Proportion of catchment on Ordovician rocks (%)	Ord
✓	✓	✓	✓	✓	✓	✓	Proportion of catchment on Silurian rocks (%)	Sil
Rainfall								
✓	✓	✓	✓	✓	✓	✓	1980-2000 mean catchment rainfall (mm/year)	Rainfall
Altitude variables								
✓	✓	✓	✓	✓	✓	✓	Mean catchment altitude (m)	dem_mean
✓	✓	✓	✓	✓	✓	✓	Maximum catchment altitude (m)	dem_max
✓	✓	✓	✓	✓	✓	✓	Minimum catchment altitude (m)	dem_min
✓	✓	✓	✓	✓	✓	✓	Catchment altitudinal range (m)	dem_range
Additional variables								
✓	✓	✓	✓	✓	✓	✓	Easting	X
✓	✓	✓	✓	✓	✓	✓	Northing	Y

Numbers of data only shown where sufficient data is available for analysis (>4 records/year for SEPA)
Grey: variable transformed (square-root) Blue: variable transformed (log(x+1))
✓ Data available for all sites NB CC1 included as TF (see 8.3.2a)

8.2.2 Variable transformation

For the purposes of regression analysis transformation of variables is often required to minimise the influence of skewed datasets on the results of the regression. The transformation process requires the application of a function to a variable in a way that the distribution of the data are altered, but the fundamental nature of the data are not: it is always possible to reverse a transformation by applying the inverse function. Common transformations include applying a power factor or a logarithm to convert skewed data to a more normal distribution; the use of pH ($-\log_{10}$(Hydrogen Ion Concentration)) rather than the raw Hydrogen ion concentration is a familiar example (Figure 8-1).

Figure 8-1 An example transformation: pH



For regression analyses transformation is particularly useful as these analyses determine *linear* trends. The strength of the trend it is possible to determine is strongly influenced if the underlying data are not from the same distribution. A normal distribution is preferred as the influence and leverage of outliers is minimised by the bulk of the data being compared being in the centre of the distribution. Transformation provides a practical way to minimise this problem displaying data on a different scale: encouraging variables fit to normal distributions without fundamentally modifying the data.

All variables were considered for transformation; any variable with a skew greater than |1| was transformed with the most appropriate transformation. This was in all cases either a square root ($y = \sqrt{x}$) or a logarithmic (using $y=\log_{10}(x+1)$) transformation. Table 8-1 indicates the transformations applied.

8.3 Exploring inter-relationships between variables

This section explores relationships between the variables in the catchment-based database. Correlation analysis is used to explore the relationships separately between 1) the forestry variables 2) the catchment variables and 3) the water chemistry variables in an attempt to understand factors that may contribute to multicollinearity (explained below). In addition, the first two components from principal components analysis are explored as a means of mapping the main driving factors within the catchment and water quality datasets. The concepts of multicollinearity and Principal

Components Analysis (PCA) are briefly explained below before the relationships within the forestry, catchment variable and water quality datasets are described.

8.3.1a Multicollinearity

Regression analysis assumes that the variables used to predict the dependant variable are *independent* from one another. In practice for environmental science applications this total independence is rarely (if ever) the case: catchment variables, for example, may well be strongly influenced but not completely controlled by factors such as their geographical location, their altitude or their proximity to the coast. As a result changes in altitude may be mirrored in other variables such as rainfall, total S deposition or even forest cover. In some cases strongly correlated variables can be removed if the data they show is well represented in another similar variable. In most cases, however, it is important to know these relationships in advance of analysis so that interpretations can be modified accordingly.

8.3.1b Principal components analysis

In the discussion in this chapter and the following, principal components analysis (PCA) is used to provide an insight into the overall relationships between large numbers of variables at a time. Principal components analysis is a useful sub branch of multivariate statistics that re-projects data from a large number of variables onto new axes. It does this by first identifying the axis that explains the greatest proportion of the data: the principal component. The second component is orthogonal to the first principal component so that it explains the greatest proportion of data left unexplained by the first. Many components, up to one less than the number of included variables, can be created with each consecutive component explaining a smaller and smaller fraction of variation within the dataset.

PCA is designed as a means of compressing a dataset and grouping variables into clusters: in the analysis below, the technique is used as a qualitative mapping of the overall dataset; a descriptive tool to identify the variables that drive the majority of the greatest and second greatest proportions of the variation within the dataset. Loading plots (such as Figure 8-2) are used to map this graphically showing the correlations between each variable of interest and the first two principal components.

8.3.2 *Forestry Variable Dataset*

8.3.2a Selection of forestry variables

In advance of statistical analysis, the relationships between the forestry variables generated in 6.5.3d, were explored by correlation and scatterplot analysis to ensure that each offered a significant contribution to the analysis.

Before this CC1 (small trees) was combined with CC2 (canopy-closed forestry) to create the variable "Total Forestry" (***TF***). The same process was applied to create the variable ***TF_o300*** the total proportion of forestry over 300m within a catchment as the sum of CC1_o300 and CC2_o300.

Table 8-2 Relationships between forestry variables

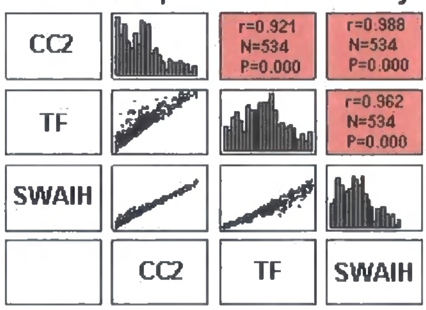


Table 8-2 compares the three forestry variables CC2, TF and SWAIH (Puhr (1997)'s structurally weighted afforestation index of height, see 6.5.3d) using all the available forestry data: it makes clear that SWAIH in particular offers little additional information than that already contained within the CC2 and TF variables (r=0.988). Regression analysis using all available CC2 data to predict SWAIH further confirms this with an R^2 of 94.45% an RMSE of 0.48m and a P<0.001; SWAIH was therefore dropped from further analysis.

The "over 300m" variables (CC2_o300; TF_o300) were not used as independent variables for regression analysis. Instead these variables were used as a means of sub-setting linear regression analyses in 8.4 so that regression was performed separately on data with different proportions of canopy-closed forestry over 300m.

Total forestry (TF) and the proportion of canopy-closed forestry (CC2) were therefore the two key variables considered for regression. The correlation between these two variables is large (0.921) and regression analysis showed an R^2 value of 0.84, RMSE 0.08 and p<0.0001. This was considered to be significantly different to warrant the investigation of both datasets: an overview of regressions between both variables and water quality indicators is presented in 8.3.4. Due to the similarity in relationships identified with water quality data the work in the remainder of this thesis uses Total Forestry as the key forestry variable.

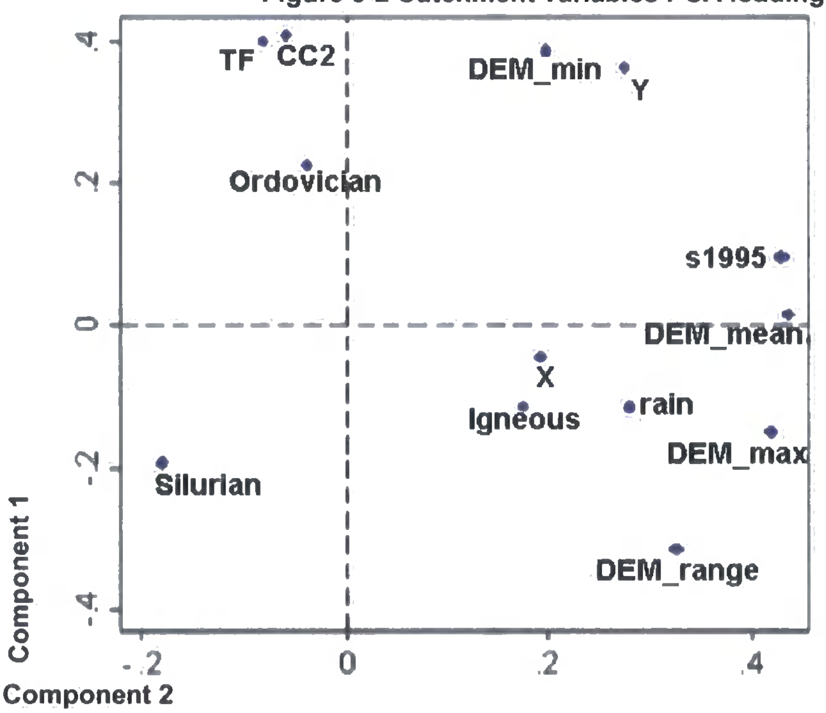
8.3.3 Non-Forestry Catchment Variables

The catchment variables listed in Table 8-1 are explored in the following section to determine the relationships that exist between them in an attempt to control for multicollinearity.

8.3.3a Principal components analysis: Catchment Variables

Figure 8-2 below shows the principal component (PC1) on the x-axis; this axis explains the greatest proportion of the variation within the catchment dataset: the y-axis is the second component (PC2); it explains the greatest proportion of the variation within the dataset once the principal components variation is taken into consideration. Figure 8-2 shows how each variable plots in terms of its correlation with these components.

Figure 8-2 Catchment variables PCA loading plot



Examining the x-axis it is clear that altitude (dem_mean, max and range) and altitude driven variables (rainfall and total S deposition) control the greatest variation within the dataset; they have the strongest correlations with the principal component. The second component (y-axis) shows stronger correlation with forestry variables (cc2, TF) and elevation minimum and range (dem_min, dem_range). The geology variables appear not to be strongly correlated with either axis. The fact that forestry variables plot independently to the majority of other variables is encouraging as it suggests a reduced likelihood that any "forest effect" identified will be a result of multicollinearity.

8.3.3b Correlations between catchment variables

Figure 8-3 Scatterplot and Correlation matrix for catchment variables

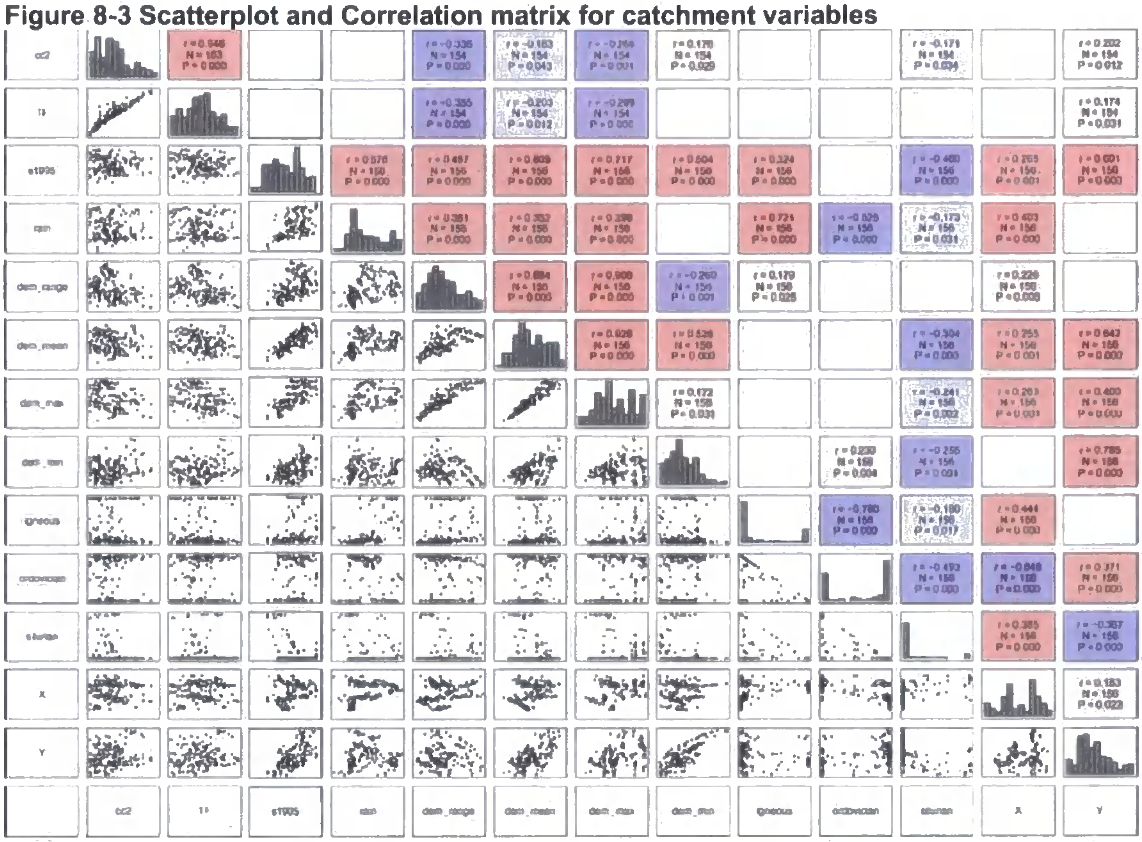


Table 8-3 Scatterplot interpretation Key

Figure 8-3 illustrates the inter-relationships between catchment variables for the linkages for which there are forestry data. There are statistically significant relationships between both TF and CC2 and a number of catchment variables; these indicate that sites with high proportions of forestry are most commonly found in more northerly, lower altitude sites with smaller ranges of catchment altitudes and higher low catchment mouths (CC2 only); they also indicate a mild bias towards Silurian geologies (CC2 only). The majority of these have relatively weak correlations with only "dem_range" showing a correlation coefficient (r) of greater than 0.3. This indicates that the impacts of these factors on an interpretation of the "forest effect" are negligible; they reflect the sampling strategy taken for the high-flow single-survey sites rather than any causal physical correlation.

Special attention was paid to determine whether any of the four altitudinal variables dem_max, dem_mean, dem_range and dem_min should be removed from the dataset. Dem_Max, Dem_mean and Dem_range all correlated significantly with correlation coefficients close to 1. However, it was determined that all variables should be preserved, and that stepwise multiple regression analysis would drop those providing the least influence.

The remainder of the relationships present are driven by the geography of the region and particularly by distance north, which correlated with increased altitude, total S deposition and decreasing proportion of Silurian rocks, and distance east, correlated with increased rainfall and decreasing proportions of Ordovician rocks. It is important to bear these relationships in mind in terms of their influences on regressions in later sections. It is also important to note that neither CC2 nor TF is significantly correlated with easting (X) and the relationship with northing (Y), though significant at $P<0.05$, is weak ($r=0.202$).

8.3.4 Water Chemistry Variables

As mentioned in section 8.2.1 eight water chemistry datasets were extracted from the catchment-based database. Within these datasets twelve chemistry variables were considered for analysis. It should be noted that the surveys from which these chemistry variables were taken differed significantly (Table 8-4).[21]

Table 8-4 Water quality surveys

Survey	Satellite Image	Flow	Geology	Catchment Size	Deposition
SEPA 1989	1989	Median	Mixed	Medium/Large	Higher
SEPA 1995	1995	Median	Mixed	Medium/Large	↓
Puhr 1995	1995	High	Single geology	Small	↓
SEPA 2001	2001	Median	Mixed	Medium/Large	↓
SEPA 2003	2003	Median	Mixed	Medium/Large	↓
SEPA 2005	2005	Median	Mixed	Medium/Large	↓
UoD 2005	2005	High	Single geology	Small	↓
UoD 2006	2005	High	Single geology	Small	Lower

Table 8-4 lists the datasets and highlights the differences that require consideration during interpretation of the results presented below. The major differences are those between the SEPA long-term and the single-date high flow data (highlighted in section 6.2). The long-term SEPA data are based on the median value of a minimum of 4 annual data points, whilst the high-flow data are targeted at extreme events: the high-flow data are therefore most likely to represent the poorest chemical conditions.

[21] "surveys" in this context are used as a term to mean "years of data"; it is recognised that the SEPA data, as a median value of many individual samples, are in fact from at least four different field surveys.

Furthermore, the SEPA data are designed for long-term monitoring and not for the analysis to which they are put in this chapter: as a result, they are not targeted at single geology and as a result their subsection by geology (see 8.5.1a below) must be interpreted with greater caution. SEPA's catchments are also much larger than the headwater catchments targeted by the high-flow single-date surveys; this is again as a result of the fact the SEPA sites were selected for long-term monitoring rather than statistical analysis. The final factor that is necessary to consider is that deposition of total S deposition has been steadily decreasing since the 1970s (see 6.5.4) this will have changed the inputs of acid anions and may affect the relationships between chemistry and forestry. It should also be noted that problems with data recording and availability (6.2.2) influenced the availability of sulphate, nitrate and DOC records for certain years of the SEPA datasets. Table 8-1 lists the variables available by survey.

One additional variable corresponding to the ratio between chloride and sodium ions (Cl μeql^{-1} /Na μeql^{-1}) was also included to determine whether any "forest effect" on sodium and chloride contributed to a significant bias in the anion/cation balance: values over 1 indicate and anion bias, below 1 a cation bias. This variable is referred to as *Cl:Na*.

8.3.4a Principal components analysis: Chemistry Variables

Figure 8-4 Loading plot: chemistry variables

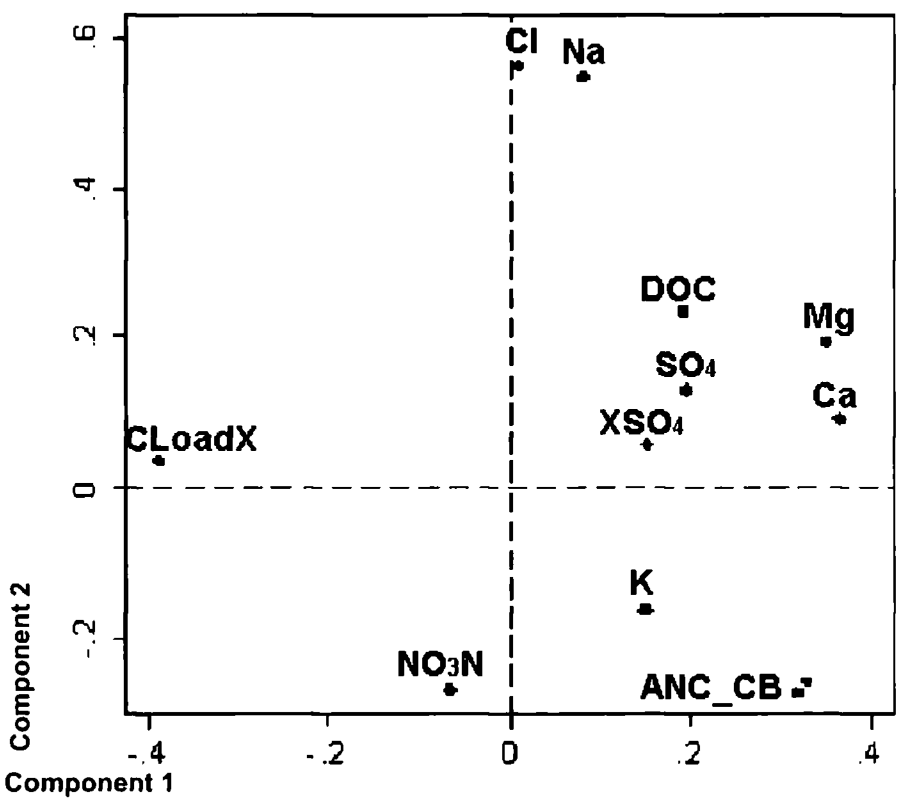


Figure 8-4 shows the loading plot for the first two PCA components of the chemistry data. In this case, the principal component explains ≈40% of the data and correlates most strongly with calcium, magnesium, pH and charge balance ANC: this indicates that the major influence is a measure of acidity, or acid influence. The second component shows a strong influence of salt deposition with high correlations with both sodium and chloride.

8.3.4a(i) Correlations between catchment variables

Figure 8-5 Scatterplot and correlation matrix for all water chemistry data

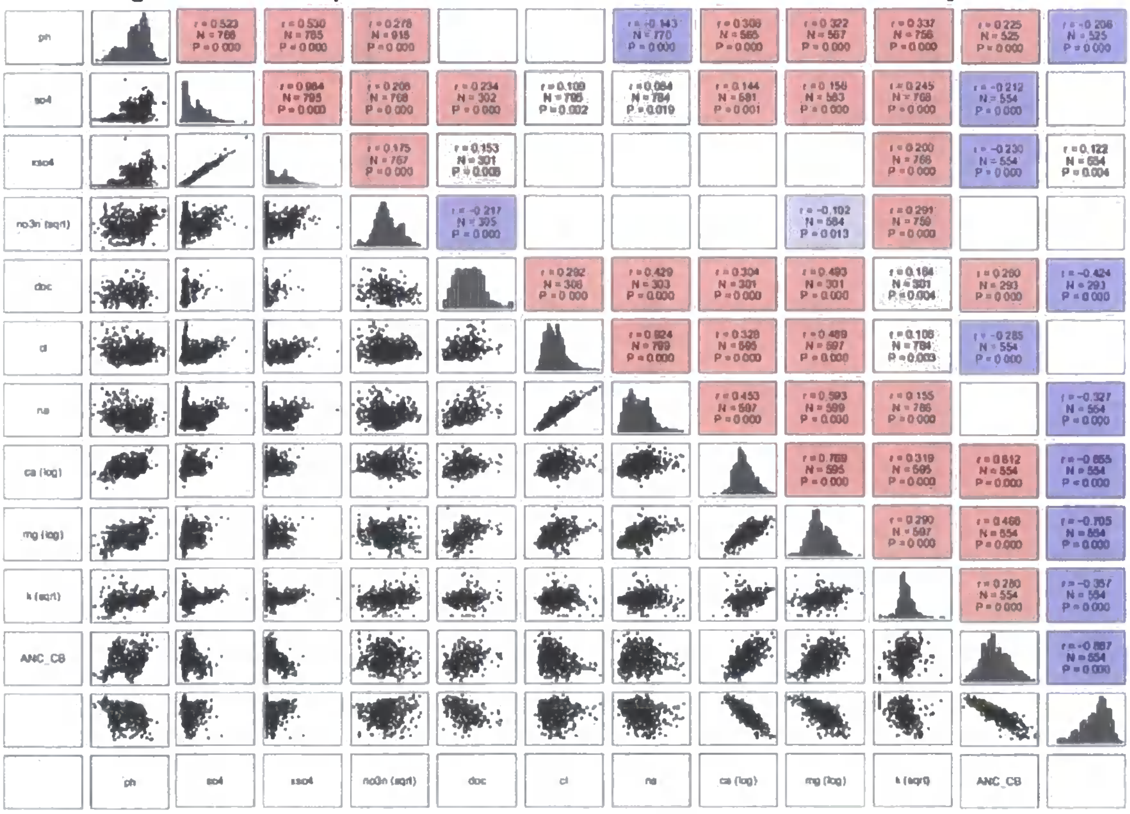


Table 8-5 Scatterplot interpretation Key

Figure 8-5 shows that water chemistry variables are significantly correlated following the acid influence trend identified in the PCA: base cations, acid anions and charge balance ANC increase and Critical Loads exceedance decreases with increasing pH. Other notable relationships include: the marine influence shown in the strong correlations between sodium and chloride ions and the lack of a significant relationship between DOC and pH. The figure is designed to produce an illustrative impression of major trends and it should be noted that many of the relationships may be non-stationary through time and survey; i.e. whilst the Cl:Na ratio will likely be constant, there is no reason for relationships with SO_4 to remain so, as sulphate is likely to be decreasing with lowering pollutant sulphate inputs. In addition, it is also notable that a large number of zero values are clear in the sea salt corrected sulphate data; this results from the correction process and is discussed below in section 8.7.1c.

It is also interesting to note that the critical load output is shown to be significantly correlated with base cations, pH and the acid anions; it is notable that the correlations with magnesium, calcium and charge balance ANC are strong ($r < -0.7$) whereas no significant relationship is identified with sulphate and the relationship with pH is weak ($r = -0.2$). This reflects the Critical Loads model's design to identify base cation buffering (*acid sensitivity*) rather than current acidic condition (*acidic waters*).

8.4 Regression Analysis

8.4.1 Introducing Regression

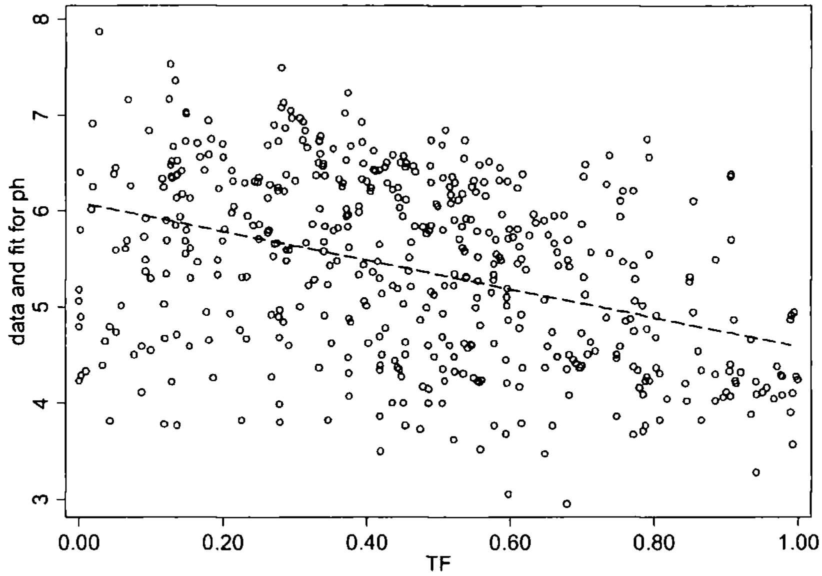
The aim of this chapter is to determine whether a "forest effect" can be identified, and whether the "forest effect" can be identified in areas outside of those in which the *Forest and Water Guidelines* apply.

Least squares regression is a statistical method that produces a linear model (Equation 8-1) that describes a relationship between a dependant variable of interest, such as a water chemistry parameter (Y) and any number of independent variables, such as forestry or other catchment variables (X).

Equation 8-1 $\mathbf{Y = k + c_1x_1 + c_2x_2 \ldots c_nx_n}$

Figure 8-6 shows an example simple linear regression where the dependant variable pH is modelled from a single independent variable, Total Forestry, along with the statistical output that describes how well the predicted line fits the observed data: these are explained in Table 8-6.

Figure 8-6 Example regression: forestry and pH (all data, unfiltered)



N = 493
R^2 = 0.1536
RMSE = .88087

ph	C	Std. Err.	t	P>|t|
TF	-1.501361	.1590535	-9.44	0.000
k	6.086963	.0838567	72.59	0.000

Table 8-6 Regression parameters

N	**N** is the statistical population; the number of data points included in the regression. As a rule of thumb there should always be 10 times as many points as the number of variables involved in the regression; in the tables that follow any regressions based on less than 10 points are highlighted in grey as a warning for careful interpretation. In the regression in Figure 8-6 there are 493 points so this is not a problem.
R^2	The proportion of the dataset explained by the regression line. R^2 values close to 1 occur when the data plot exactly on the line, close to zero there is very little trend and only scatter about the line exists. In Figure 8-6 the R^2 is 0.15 showing that 15% of the variation within the dataset is explained by the line.
RMSE	***RMSE*** (Root Mean Squared Error) is the mean scatter about the regression line expressed in the units of the modelled dataset. In Figure 8-6 the RMSE indicates that the mean scatter around the regression line is 0.88 pH units.
k	***k*** is used to indicate the y intercept of the regression line, the value at which the line crosses the y axis. In Figure 8-6 the ***k*** value (pH 6.08) would be the expected value was there to be no forestry within the catchment.
c_x	c_x is the coefficient for variable x. Each variable input into the model has its own coefficient, which will always be in the units of the input data. In a simple linear regressing such as Figure 8-6 where there is single independent variable (Total Forestry) the coefficient controls the angle of the regression line: in Figure 8-6 the coefficient (-1.5) is therefore the change in the pH that would result from a change in forest proportion from 0 – 100%
P	***P>|t|*** is a measure of the probability that the regression is caused by chance. In this thesis a relationship is described as significant when P<0.05 meaning that there is a less than 5% chance that the relationship is a result of random artefacts within the dataset. With P<0.001 the relationship in Figure 8-6 is highly statistically significant.

8.4.1a Exploring the "forest effect"

Figure 8-6 shows that there is potential evidence for a "forest effect" on water quality. The regression analysis indicates a statistically significant ($P<0.05$) relationship between the total proportion of forestry within a catchment and pH; a relationship that explains approximately 15% of the variation within the Total Forestry-pH dataset: it suggests that a fall of pH of 1.5 units could be expected with a change in forestry from 0-100%. There is however a significant amount of scatter (RMSE = 0.88 pH units) that indicates that there are a number of other contributory factors also influence the relationship. It should be noted that Figure 8-6 is not controlled for the impacts of geology and combines the results of all the water chemistry data from a variety of different surveys, both high-flow and median flow data from different years. It should therefore be seen as an encouraging indication of the potential to identify the "forest effect" by regression analysis, but without controlling for geology and survey it is impossible to interpret in more detail. The following sections explore the "forest effect" in more detail by a) performing simple linear regression on subsets of the dataset presented in Figure 8-6 to control for complicating factors and b) by exploring multiple regression to determine the relative contributions of a variety of catchment factors at once.

8.5 Simple Linear Regression

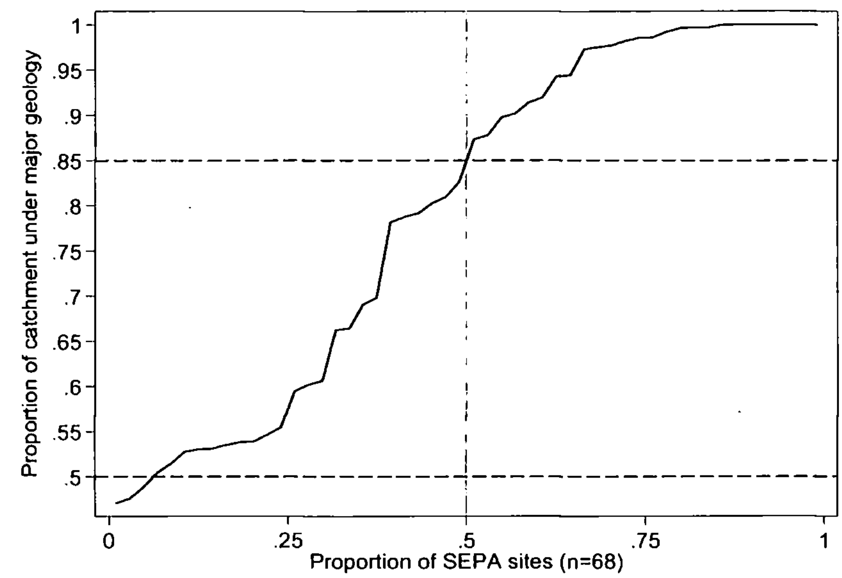
8.5.1 Controlling for complicating factors

8.5.1a Geology as acid sensitivity

Puhr (1997) identified significant improvements to forestry-water quality regression analyses by stratifying by geology as an index of acid sensitivity; this methodology is followed below by classifying sites into geology classes of igneous (most acid sensitive), Ordovician (acid sensitive) and Silurian (least acid sensitive; section 6.5.5). For the high-flow sites, which were selected to contain proportions of 95% or more of a single catchment this is easily achieved: however as raised in section 8.3.4 SEPA sites are often on mixed geologies.

Figure 8-7 shows the proportion of SEPA sites by the percentage of the catchment under the major geology. It shows that to ensure that if catchments classified so as to have over 85% of the major geology would require discarding 50% of the available data. Instead, to preserve a larger proportion of the data, sites were classified into the geology class of the geology that covered over 50% of the catchment area. As a result, it is necessary, during the interpretation process, to consider the impacts of the assumption that it is the major geology that provides the geological control on water quality. It is expected that errors that result from a misclassification of geological sensitivity are expected to stand out as outliers on the overall distribution; furthermore, the influence of geology is investigated in more detail in the multiple regression approach in section 8.7 where the proportion of each geology included as a separate variable. Figure 8-8 shows the distribution of the regional distribution of these sites: note that for the SEPA sites there is only a sufficient number of sites (N>10) to allow for the regression analysis of Ordovician sites.

Figure 8-7 Proportion of major geology

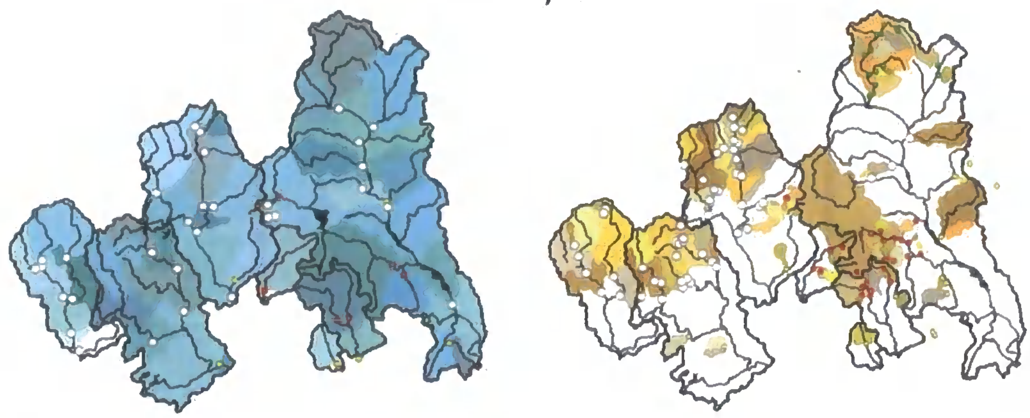


8.5.1b A note on Carsphairn

During the stakeholder meeting (Chapter 7) the area of high altitude forest in the Northern Dee (green dots in Figure 8-8) was identified as an anomaly, with unusually well buffered water quality for its mixed Ordovician/igneous geology. It was suggested that its proximity to the better buffered rocks to the north provided some additional buffering. This, in turn, suggests that classification by geology may underestimate the buffering capacity of these relatively well-buffered sites. In the following section analysis is stratified to control for the proportion of forestry over 300m. As the Carsphairn sites all contain a significant proportion of forestry over 300m the analysis below *includes* these sites as classified by geology for the analysis in section 8.5.1a but the sites, and any errors in their classification, are removed in the remainder of the analysis when with forestry over 300m are excluded.

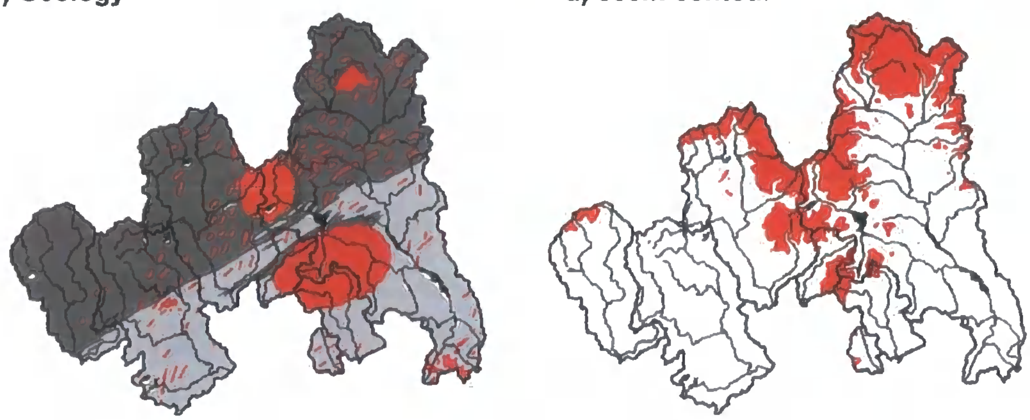
Figure 8-8 Location of study sites by geological classification

a) SEPA sites **b) UoD/Puhr Sites**



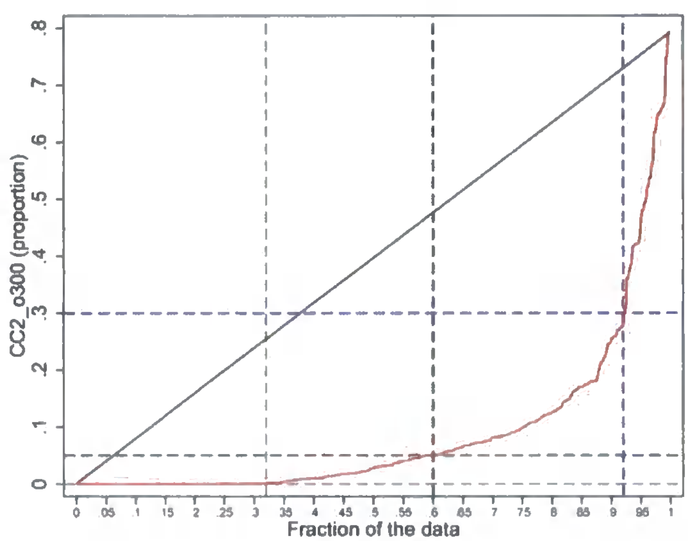
>50% Silurian > 50% Ordovician >50% igneous Carsphairn anomalous sites

c) Geology **d) 300m contour**



8.5.2 Control for proportion of forestry over 300m

Figure 8-9 proportion of forestry by over 300m



The 300m rule is a key component of the argument in support of the mechanism-down "forest effect". Chapters 2 and 7 have both shown that it is argued that, based on the best available science, it is not expected that a "forest effect" will exist below 300m, as scavenging is at its most effective in the cloud layer, which is expected to be above this level. In this chapter "high-altitude forestry" is used to refer to forestry over 300m.

In the following section linear regression analysis is performed on sub-samples of the catchment database stratified to focus on sites with low proportions of forestry above 300m as a simple test to determine whether or not a "forest effect" can be a) identified and b) identified in areas with very little or no forestry over 300m.

Figure 8-10 impacts of stratification by high-altitude forestry on regional distribution

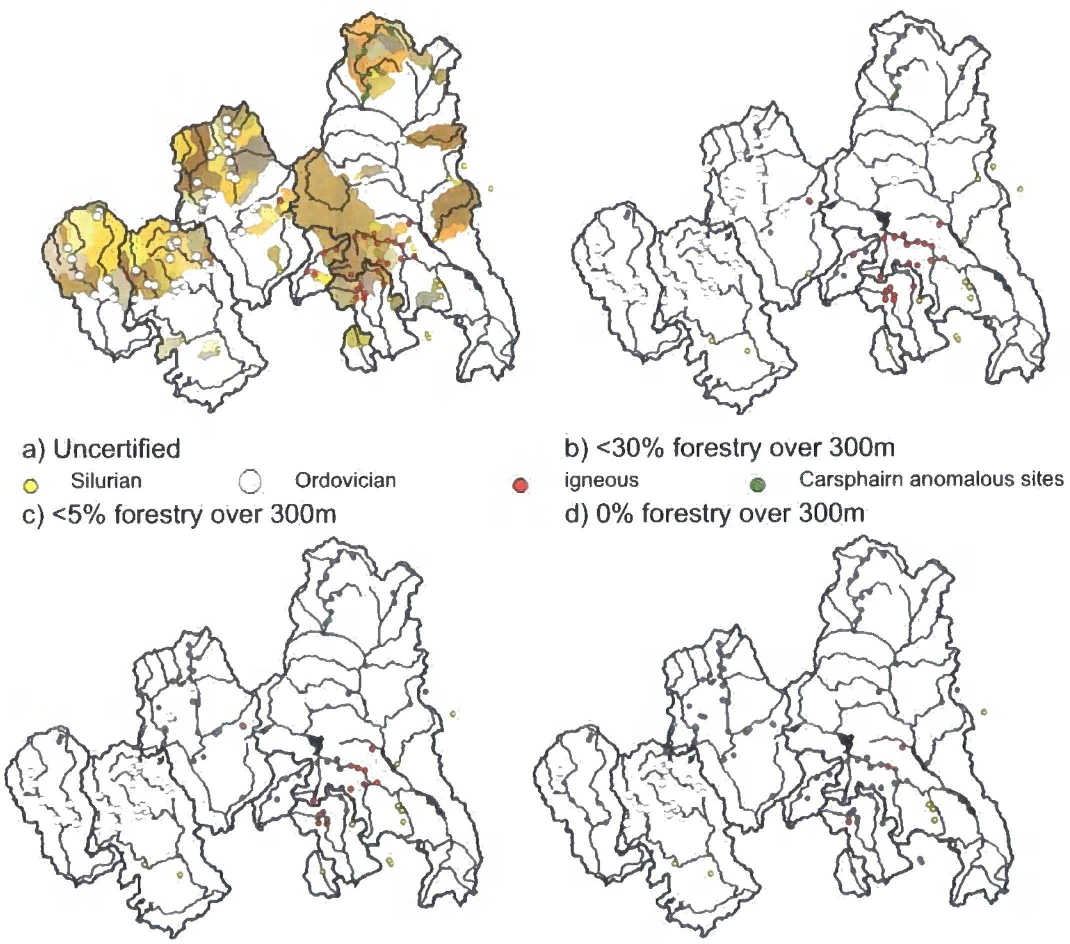


Figure 8-9 indicates the proportion of the dataset available with different levels of stratification by high-altitude forestry proportion; the smaller proportion of forestry permitted by the stratification, the less available data for analysis. To balance this the analysis that follows focuses on four stratified samples i) all sites, uncertified by high-altitude forestry (section 8.5.3a) ii) sites with less than 30% forestry over 300m (blue line; preserves ≈92% of the data) iii) sites with less than 5% forestry over 300m (black line; preserves ≈60% of the data) and iv) sites with no forestry over 300m (grey line; preserves around 30% of the data).

Figure 8-10 shows the regional impact of this stratification process: with sites with over 30% high-altitude forestry removed the most significant change is the loss of the Carsphairn sites in the Northern Dee, most Luce, Bladnoch, Cree, Fleet and southern Dee sites remain. Higher levels of stratification focus increasingly on the lowland catchments of the Bladnoch and Luce.

8.5.3 Linear regression analysis

The following sections focus on the analysis of regression overview tables: these allow the comparison of the results of many single linear regressions between a single forestry variable and the thirteen water quality variables across the eight surveys under different levels of stratification. Section 8.6 investigates the relationships with individual water chemistry variables in more detail.

8.5.3a The Overall trends

8.5.3a(i) Ordivician Sites (no 300m stratification)

Table 9-7 presents the regression overview for Ordovician sites from both the three high-flow single-date surveys and the five long-term SEPA surveys. These sites have not been filtered by high-altitude forestry proportion. A "forest effect" is clearly demonstrated in both types of survey. For the high-flow data, total forestry (TF) shows statistically significant ($P<0.05$) negative relationships with pH, charge balance ANC and potassium and positive relationships with raw sulphate, chloride, sodium and DOC. These findings mirror the "forest effect" identified through time within the academic literature (Harriman and Morrison, 1982; Stoner *et al.*, 1984; Puhr *et al.*, 2000: see also Table 3-2). In the long-term monitoring samples only the effect on pH is identified consistently; a statistically significant negative trend is present in four of the five available years of data. The absence of other relationships suggests that the "forest effect" on the other variables is only present under extreme high-flow events: furthermore, the absence of a statistically significant relationship on pH in 2006, when one is present in 2005, suggests that each extreme event is significantly different.

Table 8-7 Ordovician Sites (All) Total Forestry (TF) and Chemistry

TF

*** c -0.68 N 50 r^2 0.21	*** c 15.63 N 50 r^2 0.49	*** c 8.14 N 50 r^2 0.36	*** c 72.72 N 50 r^2 0.30	*** c 68.28 N 50 r^2 0.21	n/s N 50	n/s N 50	NO DATA	n/s N 50	n/s N 50	*** c -1.35 N 50 r^2 0.22	*** c -11.59 N 50 r^2 0.24	n/s N 50
** c -0.82 N 73 r^2 0.09	** c 4.63 N 73 r^2 0.09	n/s N 73	** c 178.48 N 73 r^2 0.10	* c 113.55 N 73 r^2 0.08	** c 0.11 N 73 r^2 0.13	n/s N 73	*** c 8.19 N 73 r^2 0.17	n/s N 73	n/s N 73	*** c -2.10 N 73 r^2 0.25	** c -5.90 N 73 r^2 0.11	n/s N 73
n/s N 71	*** c 8.43 N 71 r^2 0.16	* c -1.77 N 71 r^2 0.06	** c 116.64 N 71 r^2 0.14	*** c 123.08 N 71 r^2 0.15	n/s N 71	n/s N 71	* c 5.39 N 71 r^2 0.06	n/s N 71	** c 0.14 N 71 r^2 0.12	*** c -1.45 N 71 r^2 0.16	n/s N 71	n/s N 71
* c -1.88 N 15 r^2 0.33	n/s N 10	n/s N 10	n/s N 10	n/s N 10	n/s N 10	n/s N 10	NO DATA	* c -0.83 N 3 r^2 1.00	n/s N 3	n/s N 9	n/s N 3	n/s N 3
* c -1.32 N 21 r^2 0.25	n/s N 19	n/s N 19	n/s N 20	n/s N 20	*** c 0.28 N 20 r^2 0.48	n/s N 20	NO DATA	* c 0.49 N 4 r^2 0.97	** c 0.58 N 4 r^2 0.98	n/s N 19	n/s N 4	n/s N 4
n/s N 26	NO DATA	NO DATA	n/s N 24	n/s N 8	n/s N 8	n/s N 24	NO DATA	n/s N 8	n/s N 8	n/s N 8	NO DATA	NO DATA
** c -1.20 N 28 r^2 0.30	NO DATA	NO DATA	n/s N 28	n/s N 15	n/s N 15	n/s N 28	NO DATA	n/s N 14	n/s N 15	n/s N 15	NO DATA	NO DATA
*** c -1.81 N 28 r^2 0.39	NO DATA	NO DATA	n/s N 25	n/s N 23	n/s N 22	* c -2.94 N 25 r^2 0.26	n/s N 21	n/s N 23	n/s N 23	n/s N 22	NO DATA	NO DATA

Table 8-8 Ordovician Sites (All) Canopy-closed Forestry (CC2) and Chemistry

cc2

** c -0.69 N 50 r^2 0.18	*** c 16.71 N 50 r^2 0.47	*** c 9.82 N 50 r^2 0.43	*** c 66.92 N 50 r^2 0.21	* c 56.85 N 50 r^2 0.12	n/s N 50	n/s N 50	NO DATA	* c -0.19 N 50 r^2 0.09	n/s N 50	** c -1.30 N 50 r^2 0.17	*** c -13.88 N 50 r^2 0.28	n/s N 50
* c -0.79 N 73 r^2 0.07	** c 5.60 N 73 r^2 0.11	n/s N 73	** c 198.37 N 73 r^2 0.10	* c 124.29 N 73 r^2 0.08	** c 0.12 N 73 r^2 0.13	n/s N 73	*** c 8.50 N 73 r^2 0.15	n/s N 73	n/s N 73	*** c -2.33 N 73 r^2 0.25	** c -6.44 N 73 r^2 0.11	n/s N 73
n/s N 71	*** c 9.29 N 71 r^2 0.15	n/s N 71	** c 125.55 N 71 r^2 0.12	*** c 132.67 N 71 r^2 0.14	n/s N 71	n/s N 71	n/s N 71	n/s N 71	** c 0.15 N 71 r^2 0.12	*** c -1.63 N 71 r^2 0.17	n/s N 71	n/s N 71
* c -2.48 N 15 r^2 0.37	n/s N 10	n/s N 10	n/s N 10	n/s N 10	n/s N 10	n/s N 10	NO DATA	n/s N 3	n/s N 3	n/s N 9	n/s N 3	n/s N 3
n/s N 21	n/s N 19	n/s N 19	n/s N 20	n/s N 20	*** c 0.45 N 20 r^2 0.59	n/s N 20	NO DATA	* c 0.59 N 4 r^2 0.94	** c 0.71 N 4 r^2 0.99	n/s N 19	n/s N 4	n/s N 4
n/s N 26	NO DATA	NO DATA	n/s N 24	* c 358.05 N 8 r^2 0.51	n/s N 8	n/s N 24	NO DATA	n/s N 8	n/s N 8	n/s N 8	NO DATA	NO DATA
** c -1.46 N 28 r^2 0.28	NO DATA	NO DATA	n/s N 28	n/s N 15	n/s N 15	n/s N 28	NO DATA	n/s N 14	n/s N 15	n/s N 15	NO DATA	NO DATA
*** c -2.25 N 28 r^2 0.39	NO DATA	NO DATA	n/s N 25	n/s N 23	n/s N 22	** c -3.70 N 25 r^2 0.26	n/s N 21	n/s N 23	n/s N 23	n/s N 22	NO DATA	NO DATA

	Positive trend		Less than 10 data points		Negative trend
*	P<0.05	**	P<0.01	***	P<0.001

A comparison of Table 8-7 and Table 8-8 shows that CC2 and TF shows very similar relationships with water chemistry variables in terms of direction and strength: as a result the following chapter focuses on the analysis of the Total Forestry variable TF rather than CC2. TF was chosen as it produced higher R^2 values with chemistry variables and so to be slightly more sensitive to the "forest effect". It should be noted that the similarity between the two variables is likely to result from the structure of the forestry within the Galloway catchments during the period of study: for the most part, catchments are either canopy-closed or felled; there is little establishing forestry. As a result the differences in the distributions between the CC2 and TF, and therefore the regressions they produce are minimal. This is not thought to indicate that forest structural information provides no additional information in general; further research in an area with establishing forestry would be needed to investigate this.

8.5.3a(ii) Igneous and Silurian geologies (no 300m stratification)

There are too few sites on igneous or Silurian geologies for trends to be identified in the SEPA long-term dataset. Trends presented below are only for the high-flow samples. The legend for the graphs is on page 234.

Table 8-9 Igneous and Silurian geologies (unstratified by high altitude forestry)

TF												
** c −0.34 N 29 r^2 0.30	*** c 20.35 N 29 r^2 0.55	*** c 10.10 N 29 r^2 0.48	*** c 99.49 N 29 r^2 0.39	*** c 83.72 N 29 r^2 0.33	** c 0.14 N 29 r^2 0.27	n/s N 29	NO DATA	n/s N 29	n/s N 29	** c −1.72 N 29 r^2 0.29	*** c −13.46 N 29 r^2 0.34	n/s N 29
** c −0.49 N 28 r^2 0.24	*** c 6.64 N 28 r^2 0.38	n/s N 28	*** c 201.13 N 28 r^2 0.67	*** c 122.23 N 28 r^2 0.61	*** c 0.17 N 28 r^2 0.54	* c −1.76 N 28 r^2 0.15	n/s N 28	n/s N 28	n/s N 26	** c −2.91 N 28 r^2 0.25	*** c −8.53 N 26 r^2 0.37	n/s N 26
*** c −0.73 N 28 r^2 0.39	*** c 8.31 N 28 r^2 0.49	*** c −3.39 N 28 r^2 0.57	*** c 122.15 N 28 r^2 0.45	*** c 97.14 N 28 r^2 0.39	*** c 0.11 N 28 r^2 0.35	n/s N 27	n/s N 28	n/s N 28	n/s N 28	n/s N 28	** c −5.91 N 27 r^2 0.25	n/s N 27

TF												
** c −2.07 N 14 r^2 0.45	n/s N 14	n/s N 14	n/s N 14	n/s N 14	n/s N 14	n/s N 14	NO DATA	n/s N 13	n/s N 14	** c −2.39 N 14 r^2 0.48	n/s N 13	n/s N 13
n/s N 13	n/s N 13	n/s N 13	n/s N 13	n/s N 13	* c 0.29 N 13 r^2 0.34	n/s N 13	n/s N 13	n/s N 12	* c −0.47 N 13 r^2 0.36	* c −1.72 N 13 r^2 0.39	n/s N 12	n/s N 12
n/s N 14	n/s N 14	n/s N 14	n/s N 14	n/s N 14	n/s N 14	n/s N 14	n/s N 14	n/s N 13	n/s N 14	n/s N 14	n/s N 13	n/s N 13

A similar "forest effect" to that identified on Ordovician geologies is also present on the igneous sites (Table 8-9a): pH and charge balance ANC decrease and sulphate, chloride and sodium concentrations increase with forest cover. Furthermore, the relationships on igneous rocks explain a greater proportion of the datasets (higher R^2) than on Ordovician rocks. There is also evidence for a stronger acid anion bias in the sodium chloride ratio *cl:na* which shows a significant positive trend in each of the three surveys.

Silurian sites (Table 8-9b) show very few significant relationships. As Silurian geologies are expected to be the best buffered this is expected; however, there are very few sites sampled on Silurian geologies making firm conclusions difficult to draw. That noted, the few trends identified do match with "forest effect" identified on the other geologies: further investigation would be required to determine conclusively if a "forest effect" is present on Silurian geologies; Silurian trends are not further investigated within this thesis.

8.5.3b Under 300m

Table 8-10 and Table 8-11 show that a statistically significant "forest effect" is not restricted to sites with less than 30% forestry above 300m: the effect on pH, sulphate, chloride, sodium, potassium and, for 2005, DOC is present even in sites with very low proportions of high-altitude forestry; this is true for both Ordovician and igneous geologies. It should be noted that the lack of relationships with the Puhr 1995 data and high-flow sites with 0% forestry is expected to be due to paucity of data (N≤10) rather than demonstrating a real change in trend.

Furthermore, for the Ordovician sites, the removal of sites with over 30% forestry above 300m actually increases the number of statistically significant trends in pH detected; there is now a weak but significant trend identified in 2006. This is due to the removal of the better buffered but highly afforested Carsphairn sites (8.5.1b see Figure 8-10). The under 30% high altitude forestry relationship with pH is also clear in the SEPA long-term data for Ordovician sites for the five years of available data (Figure 8-10b).

These findings therefore support the view of a wider "forest effect" than that presented by the mechanism-down "forest effect" of the *Forest and Water Guidelines*. It is therefore clear that the 300m rule, rather than being a means of focussing down on areas at risk, is actually a factor that prevents areas identified as at risk by local knowledge being targeted for sensitive management.

Table 8-10 Ordovician sites (stratified)

a) high-flow sites with under 30% catchment forestry over 300m

TF

*** c -0.75 N 41 r^2 0.26	*** c 17.58 N 41 r^2 0.57	*** c 8.33 N 41 r^2 0.37	*** c 89.82 N 41 r^2 0.40	*** c 89.74 N 41 r^2 0.33	n/s N 41	* c 0.78 N 41 r^2 0.10	NO DATA	n/s N 41	n/s N 41	* c -0.65 N 41 r^2 0.14	*** c -11.23 N 41 r^2 0.24	n/s N 41
** c -1.18 N 53 r^2 0.17	*** c 7.08 N 53 r^2 0.22	n/s N 53	*** c 284.44 N 53 r^2 0.27	*** c 180.17 N 53 r^2 0.24	** c 0.11 N 53 r^2 0.14	n/s N 53	*** c 10.71 N 53 r^2 0.27	n/s N 53	** c 0.15 N 53 r^2 0.13	*** c -2.33 N 53 r^2 0.35	** c -6.58 N 53 r^2 0.13	n/s N 53
* c -0.94 N 51 r^2 0.12	*** c 13.15 N 51 r^2 0.38	* c -1.77 N 51 r^2 0.09	*** c 195.59 N 51 r^2 0.44	*** c 194.86 N 51 r^2 0.41	n/s N 51	n/s N 51	n/s N 51	n/s N 51	** c 0.16 N 51 r^2 0.15	*** c -1.55 N 51 r^2 0.19	** c -6.77 N 51 r^2 0.17	n/s N 51

b) SEPA long-term pH with under 30% catchment forestry over 300m

* c -2.09 N 14 r^2 0.40	* c -1.41 N 20 r^2 0.28	* c -0.79 N 25 r^2 0.16	** c -1.22 N 27 r^2 0.31	*** c -1.83 N 27 r^2 0.39

c) high-flow sites with under 5% catchment forestry over 300m

TF

** c -0.44 N 18 r^2 0.37	*** c 15.15 N 18 r^2 0.61	*** c 8.64 N 18 r^2 0.53	** c 63.22 N 18 r^2 0.36	** c 61.10 N 18 r^2 0.36	n/s N 18	n/s N 18	NO DATA	n/s N 18	n/s N 18	*** c -1.64 N 18 r^2 0.78	* c -8.39 N 18 r^2 0.23	n/s N 18
*** c -1.59 N 32 r^2 0.35	* c 5.59 N 32 r^2 0.20	n/s N 32	*** c 212.54 N 32 r^2 0.32	*** c 144.51 N 32 r^2 0.29	n/s N 32	n/s N 32	*** c 11.05 N 32 r^2 0.54	n/s N 32	n/s N 32	*** c -2.81 N 32 r^2 0.51	** c -7.18 N 32 r^2 0.21	n/s N 32
** c -1.24 N 31 r^2 0.28	*** c 13.05 N 31 r^2 0.42	n/s N 31	*** c 181.72 N 31 r^2 0.55	*** c 184.59 N 31 r^2 0.54	n/s N 31	* c 1.47 N 31 r^2 0.15	n/s N 31	n/s N 31	* c 0.15 N 31 r^2 0.18	** c -1.81 N 31 r^2 0.27	*** c -7.74 N 31 r^2 0.35	n/s N 31

d) high-flow sites with 0% catchment forestry over 300m

TF

n/s N 10	* c 12.84 N 10 r^2 0.48	n/s N 10	n/s N 10	n/s N 10	n/s N 10	* c 1.37 N 10 r^2 0.56	NO DATA	n/s N 10	n/s N 10	*** c -1.50 N 10 r^2 0.77	n/s N 10	n/s N 10
** c -1.98 N 15 r^2 0.50	n/s N 15	n/s N 15	* c 207.25 N 15 r^2 0.28	* c 150.99 N 15 r^2 0.37	n/s N 15	n/s N 15	** c 10.21 N 15 r^2 0.49	n/s N 15	n/s N 15	*** c -3.71 N 15 r^2 0.76	* c -9.53 N 15 r^2 0.27	n/s N 15
** c -2.04 N 14 r^2 0.55	n/s N 14	n/s N 14	** c 182.11 N 14 r^2 0.53	*** c 193.88 N 14 r^2 0.67	n/s N 14	n/s N 14	n/s N 14	n/s N 14	n/s N 14	*** c -2.81 N 14 r^2 0.68	** c -7.87 N 14 r^2 0.46	n/s N 14

Table 8-11 Igneous sites (stratified)
a) with under 30% catchment forestry over 300m

TF

*** c -0.36 N 24 r^2 0.39	*** c 21.31 N 24 r^2 0.66	*** c 10.60 N 24 r^2 0.57	*** c 104.04 N 24 r^2 0.48	*** c 87.01 N 24 r^2 0.47	** c 0.14 N 24 r^2 0.35	n/s N 24	NO DATA	n/s N 24	n/s N 24	** c -1.75 N 24 r^2 0.37	*** c -13.40 N 24 r^2 0.42	n/s N 24
* c -0.74 N 26 r^2 0.21	*** c 6.66 N 26 r^2 0.42	n/s N 26	*** c 216.00 N 26 r^2 0.70	*** c 128.72 N 26 r^2 0.65	*** c 0.20 N 26 r^2 0.57	n/s N 26	n/s N 26	n/s N 26	n/s N 24	* c -2.72 N 26 r^2 0.23	** c -10.60 N 24 r^2 0.30	n/s N 24
** c -0.93 N 26 r^2 0.28	*** c 8.81 N 26 r^2 0.55	*** c -4.10 N 26 r^2 0.43	*** c 133.38 N 26 r^2 0.49	*** c 106.31 N 26 r^2 0.43	*** c 0.12 N 26 r^2 0.38	n/s N 25	n/s N 26	n/s N 26	n/s N 26	n/s N 26	* c -8.99 N 25 r^2 0.23	n/s N 25

b) with under 5% catchment forestry over 300m

TF

* c -0.31 N 14 r^2 0.29	*** c 24.61 N 14 r^2 0.77	*** c 11.16 N 14 r^2 0.59	*** c 130.65 N 14 r^2 0.70	*** c 89.52 N 14 r^2 0.63	*** c 0.20 N 14 r^2 0.70	n/s N 14	NO DATA	n/s N 14	* c 0.10 N 14 r^2 0.31	** c -1.78 N 14 r^2 0.46	** c -16.37 N 14 r^2 0.54	n/s N 14
n/s N 16	*** c 9.40 N 16 r^2 0.71	n/s N 16	*** c 253.78 N 16 r^2 0.86	*** c 154.52 N 16 r^2 0.79	*** c 0.21 N 16 r^2 0.68	n/s N 16	n/s N 16	n/s N 16	n/s N 15	n/s N 16	* c -9.59 N 15 r^2 0.39	n/s N 15
n/s N 16	*** c 10.85 N 16 r^2 0.68	*** c -4.30 N 16 r^2 0.76	*** c 177.59 N 16 r^2 0.81	*** c 141.89 N 16 r^2 0.72	** c 0.15 N 16 r^2 0.46	n/s N 15	n/s N 16	* c 0.19 N 16 r^2 0.26	* c 0.13 N 16 r^2 0.35	n/s N 16	n/s N 15	n/s N 15

c) with 0% catchment forestry over 300m

TF

n/s N 10	* c 12.84 N 10 r^2 0.48	n/s N 10	n/s N 10	n/s N 10	n/s N 10	* c 1.37 N 10 r^2 0.55	NO DATA	n/s N 10	n/s N 10	*** c -1.50 N 10 r^2 0.77	n/s N 10	n/s N 10
** c -1.98 N 15 r^2 0.50	n/s N 15	n/s N 15	* c 207.25 N 15 r^2 0.28	* c 150.99 N 15 r^2 0.37	n/s N 15	n/s N 15	** c 10.21 N 15 r^2 0.49	n/s N 15	n/s N 15	*** c -3.71 N 15 r^2 0.76	* c -9.53 N 15 r^2 0.27	n/s N 15
** c -2.04 N 14 r^2 0.55	n/s N 14	n/s N 14	** c 182.11 N 14 r^2 0.53	*** c 193.86 N 14 r^2 0.67	n/s N 14	n/s N 14	n/s N 14	n/s N 14	n/s N 14	*** c -2.81 N 14 r^2 0.68	** c -7.67 N 14 r^2 0.46	n/s N 14

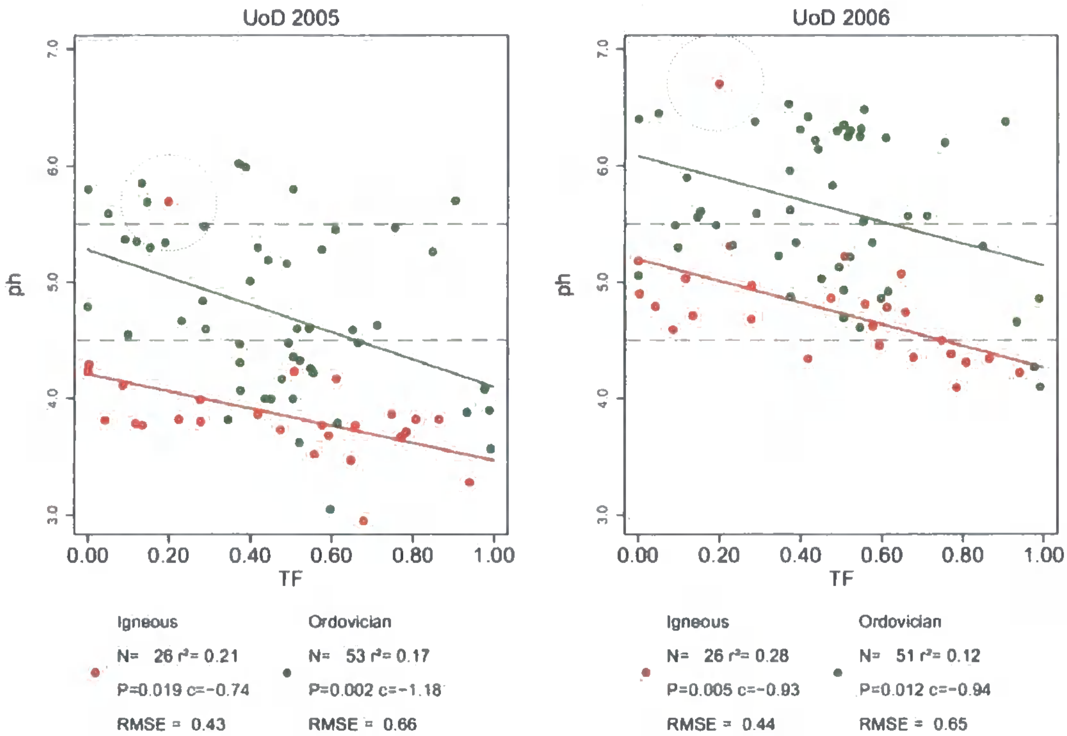
8.6 Comparing Individual variables

The previous section provided an overview of the "forest effect" as a factor leading to a decrease in pH, charge balance ANC and potassium and an increase in sulphate chloride, sodium and DOC. The following sections address each of these variables individually. All graphs and statistics shown are drawn from the sample stratified to under 30% high altitude forestry: as such, none of the graphs would be expected to show a "forest effect" under a literal interpretation of the *Forest and Water Guidelines*.

8.6.1 pH

pH is a direct measure of acidity in terms of the hydrogen ion concentration of the water ($-\log_{10}[H^+]$); it is a common indicator of the overall acid/base status of a system with low pH conditions indicating acidic waters: Harriman (1988) describes a pH 5.5 as the biologically critical level for fish with fisheries impacts becoming severe at pH 4.5 (see Table 3-1).

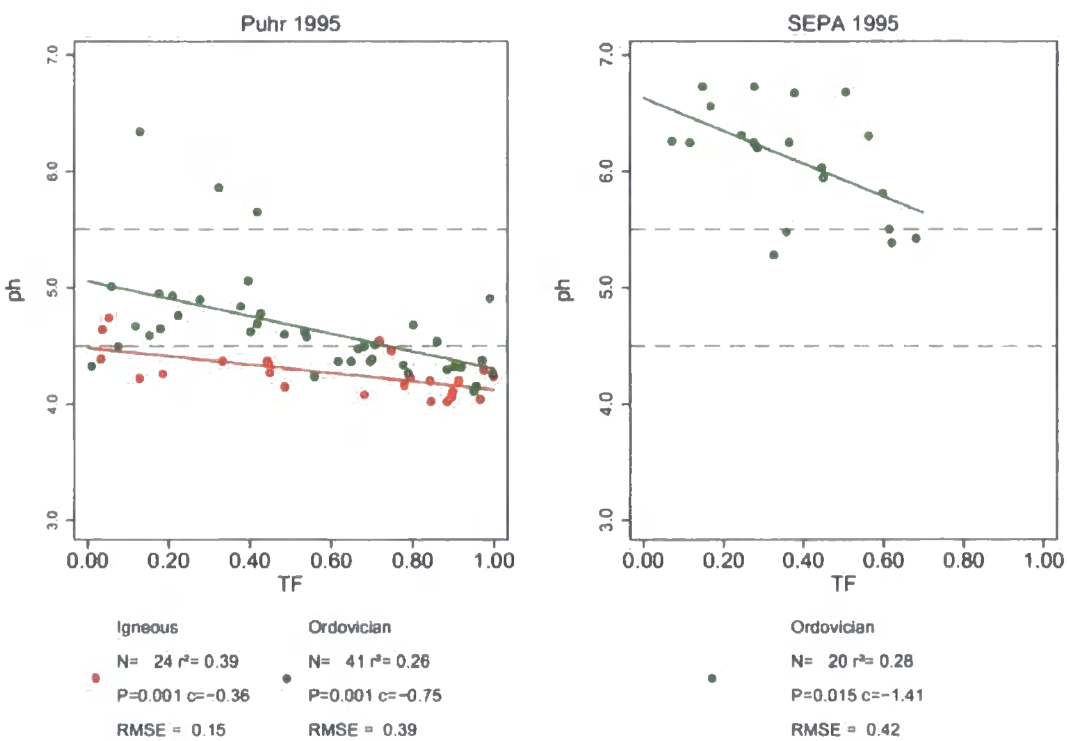
Figure 8-11 linear regression relationship between pH and forestry (under 30% high altitude forestry). Area ringed in grey is an outlier from the Carsphairn system which is thought to be better buffered than its igneous geology suggests due to overlying drift.



Examining the regression coefficients (c) shown in Table 8-10 and 8-11 we see that an increase in forestry from 0 – 100% would be expected to lead to a decrease in pH of 0.75 < c < 1.18 and 0.36 < c < 0.93 high-flow pH units for Ordovician and igneous geologies respectively. For Ordovician geologies the SEPA data indicate that median flow pH would be expected to reduce by 0.79 < c < 2.09. These values should be interpreted with care as there is significant scatter around these lines; whilst all relationships are statistically significant the proportion of the dataset explained by the relationships are low ($R^2 < 0.4$ for all surveys and all geologies). This is to be expected; the "forest effect" is an additional exacerbatory factor that contributes to more acidic water quality: it is not the sole cause of surface water acidification within the catchment. This does not however diminish its significance; Figure 8-11a shows that, for 2005, no sites on Ordovician geologies with under 30% total forestry have a pH below the critical threshold of pH 4.5 whilst many sites with greater proportions of forestry do. The effect's ecological significance cannot therefore be ignored.

Comparing the two contemporary surveys (Figure 8-11a) highlights the differences between events; the 2005 event (which the results in 8.6.2 and 8.6.3 below suggest has a greater sea salt influence) has considerably lower pH than the 2006 event. It is important to note that, despite this difference in severity, the coefficients of the regression lines do not vary greatly and the "forest effect" is statistically significant in both years. The clear igneous outlier (circled in grey) in both graphs is a site from the Carsphairn system; its removal significantly reduces the regression coefficient to -0.3 (2005) and -0.5 (2006): the significance of the line is not, however, altered.

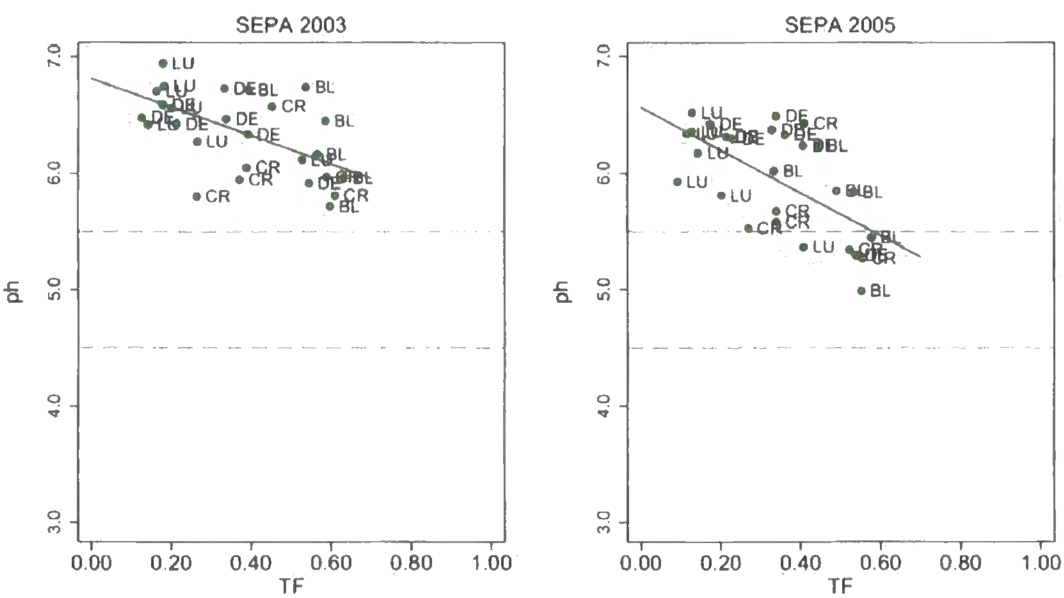
Figure 8-12 Regression graphs for pH and Total Forestry in 1995 comparing high-flow and long-term surveys.



Comparing the contemporary high flow surveys (Figure 8-11) with 1995 data (Figure 8-12) suggests that the "forest effect" has increased in scatter: the 1995 data has much lower RMSE for both Ordovician and igneous rocks. This may be an indication that the "forest effect" had a greater control on water quality under past deposition conditions however differences between surveys and rainfall events make this difficult to interpret this further. Nevertheless, comparing the data for 2005 and 1995 it is clear that low pH (<4.5) events continue to occur in Galloway, and that these are worse under forestry.

Figure 8-12 shows the difference between high-flow and annual median-flow data. A "forest effect" is notable on both. For the median-flow data the "forest effect" has a steeper coefficient. This is expected due to the pH scale's logarithm function, as well as the fact that high flow conditions are expected to be poor in advance of the "forest effect". As a result, overall median-flow pH is higher (less acidic): nonetheless, in forested areas median-flow pH shown to drop below the critical limit of 5.5 in both the 1995 and 2005 data (Figure 8-13). The existence of a "forest effect" on median-flow chemistry suggests that the "forest effect" is not just restricted to extreme events. Figure 8-13 confirms that the effect is still present in contemporary data, but that inter-annual variations are to be expected: the "forest effect" has a greater coefficient in 2005 than 2003, and more sites are reduced below pH 5.5. Figure 8-13 also shows that the effect is well distributed across catchments: the forest site in the otherwise moorland Luce provides a good example of this; it plots separately from the other Luce sites showing evidence of the "forest effect" in 2005 (grey ring).

Figure 8-13 contemporary long-term SEPA data



Ordovician
N= 27 r^2= 0.31
P=0.003 c=-1.22
RMSE = 0.32

Ordovician
N= 27 r^2= 0.39
P=0.000 c=-1.83
RMSE = 0.36

Labels by catchment BL=Bladnoch; CR=Cree; DE=Dee; FL=Fleet; LU=Luce

8.6.2 *Sulphate, Sea salt Corrected Sulphate and Critical Loads*

Figure 8-14 Linear regression between Total Sulphate and Total Forestry, a comparison between 1995 and 2006 surveys (SO_4 units: μeql^{-1})

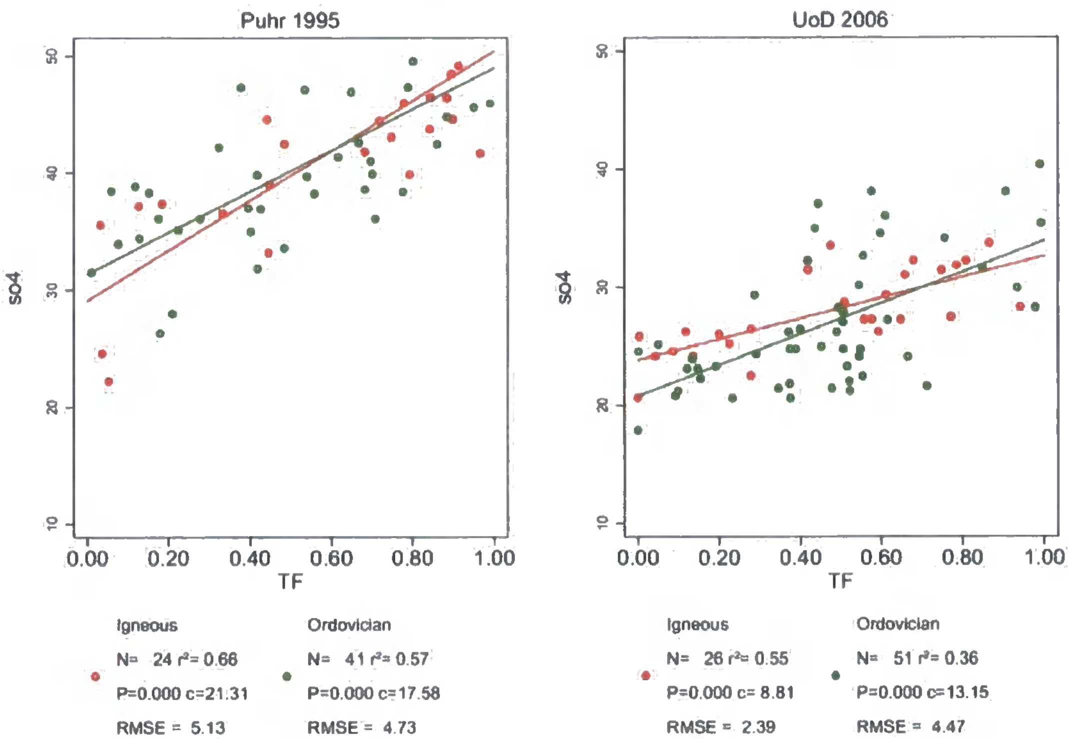


Figure 8-14 shows the relationship between raw freshwater sulphate and forestry cover; the "forest effect" shown can be seen as the "scavenging" mechanism represented in the *Forest and Water Guidelines*. Although comparisons between events are difficult both the coefficient of the line and the overall amount of sulphate scavenged has decreased between the 1995 and contemporary surveys (the 2005 survey shows a similar trend and a lower regression coefficient; see section 8.5.3a). This matches with the expected decline in sulphate deposition (NEGTAP, 2001) and the findings of Chapter 9.

Figure 8-15 Comparison between regression analyses for sea salt corrected sulphate (xSO_4) and Total Forestry in 1995 and 2006. Evidence of over-correction during the sea-salt correction process is shown for the 2006 data (xSO_4 units: μeql^{-1}).

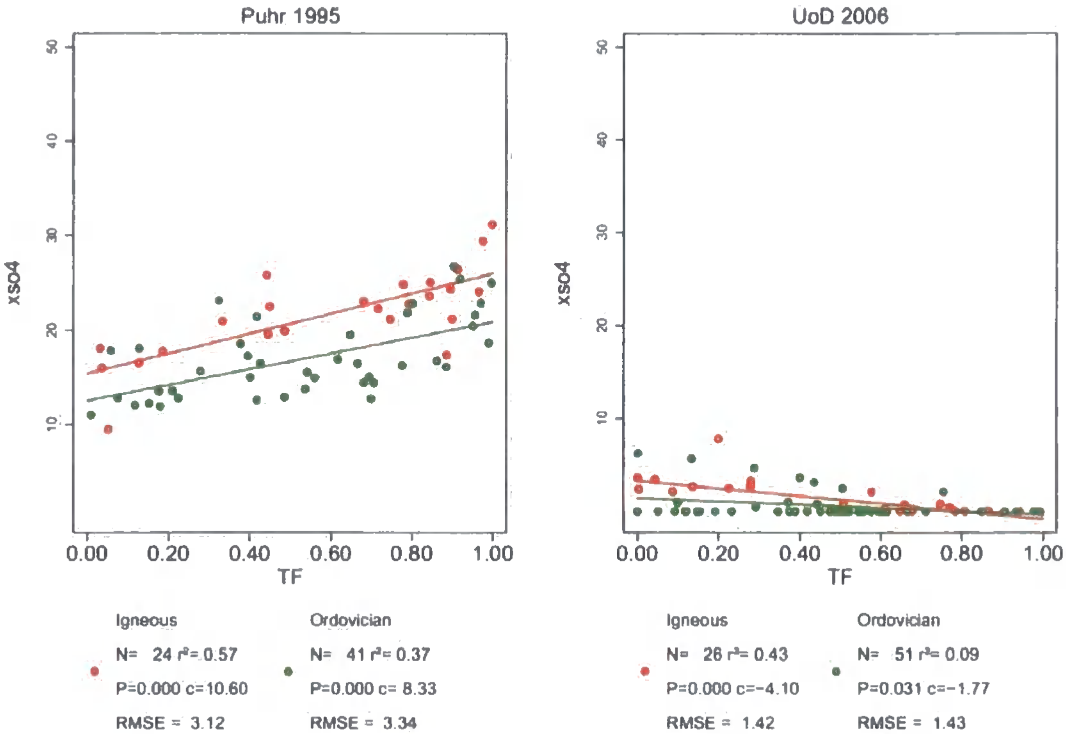
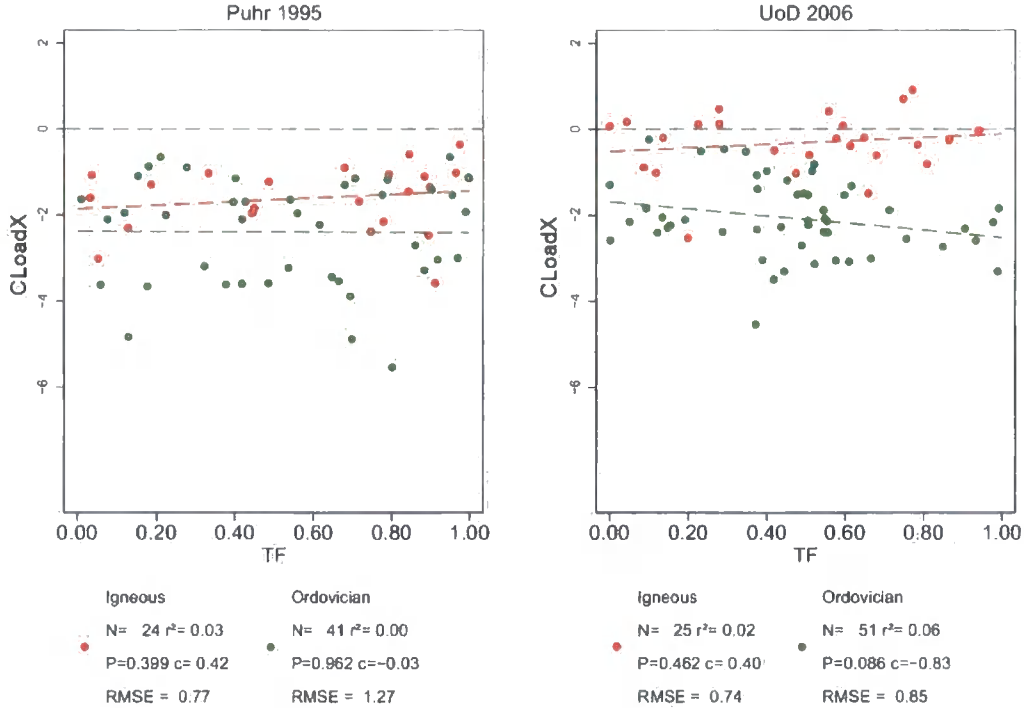


Figure 8-15 shows the same data for sea salt corrected sulphate (xSO_4); as explained in 3.2.6a(iv) these values are corrected to the 'anthropogenic contribution to sulphate' by removing sulphate in relation to the amount of chloride within a water sample. Whilst, the 1995 data continues to show a "forest effect" in xSO_4, of particular note is the impact on the 2006 data: the high levels of chloride within both the 2005 and 2006 (see also Table 8-10) samples mean that the sulphate contribution is masked entirely. In 2005 this leads to no trend being identified, and in 2006 a negative trend is identified where a positive trend in raw sulphate exists.

Clearly, in maritime areas, during high-flow events the sea salt correction needs to be considered very carefully, as it is unlikely that these zero values are a true reflection of the anthropogenic sulphate deposition. This has significant implications for the use of the Critical Loads model at high-flow as put forward by the *Forest and Water Guidelines* in these areas, particularly as sea salt events are likely to be amongst the most significant in terms of ecological impacts (Laudon, 2008). Furthermore it is clear that raw sulphate is showing a "forest effect": if using sea salt corrected sulphate is masking this effect raises questions as to whether the approach is appropriate as a means to identify the "forest effect" for management purposes.

Figure 8-16 Comparison of regression analyses between Critical Loads exceedance and Total Forestry for 1995 and 2006 (CLoadX units: keq ha^{-1}yr^{-1})



Further questions are raised regarding the application of the Critical Loads exceedance for identifying areas at risk from the "forest effect" by Figure 8-16; in contrast to acidity indicator variables such as pH, sulphate and charge balance ANC, Critical Loads exceedances do not show a statistically significant "forest effect". This adds further credence to the wider "forest effect" of local stakeholders; it suggests that the Critical Loads model in its current form is an inappropriate tool for the identification of areas at risk (Cf. Wynne, 1992; 2.2.1c), and that, by privileging the model as a way of understanding the environment focus was taken *away* from areas correctly identified as at risk by local knowledge. As a result the use of the Critical Loads model is shown to be a factor that restricts decision maker's access to Best Available Knowledge.

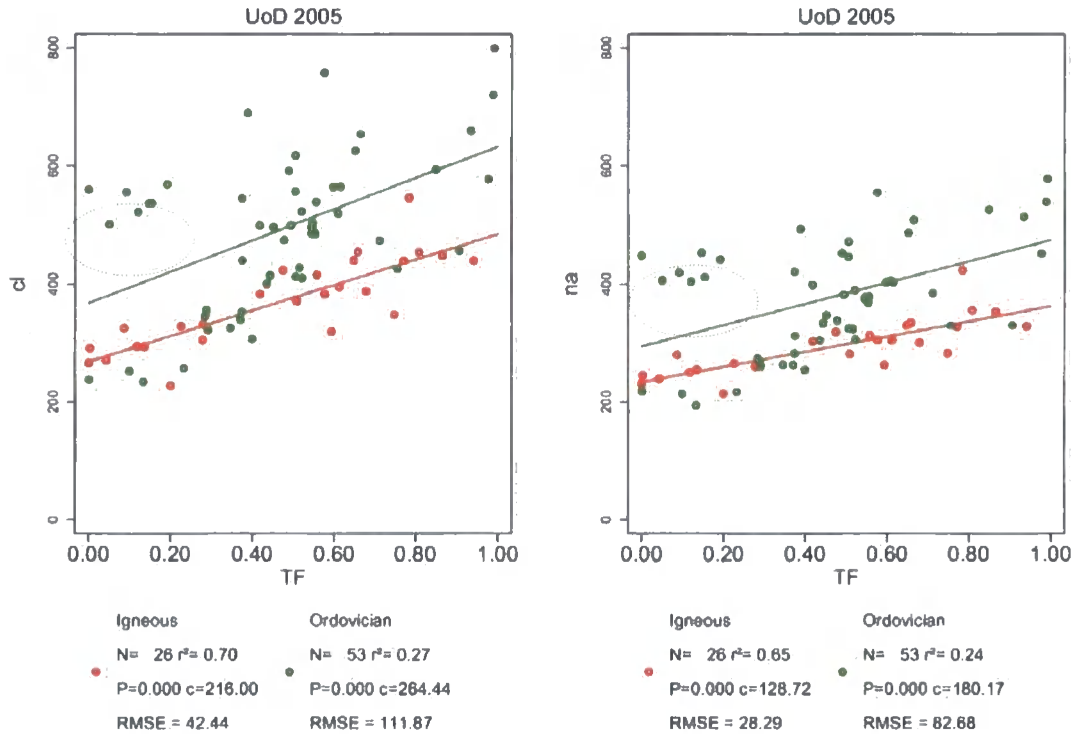
The extent to which it is the individual event that influences the applicability of the Critical Loads approach has not been explored here; changes in event would not be expected to alter the spatial distribution of exceedances (compare 1995 and 2006 in section 7.2.2), but may alter the number of sites that pass or fail: for the model to be used as a management tool, this variability would also need to be taken into consideration.

8.6.3 Marine Ions

Both chloride and sodium ions show statistically significant relationships with forestry (8.5.3a) with large coefficients indicating an increase of 89 < c < 264 μeql^{-1} high-flow chloride and 89 < c < 194 μeql^{-1} high-flow sodium on Ordovician sites and 104 < c <

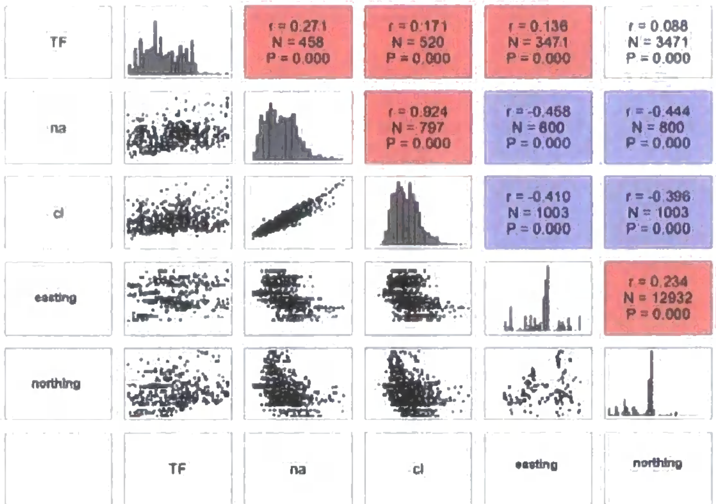
216 μeql^{-1} high-flow chloride and 87 < c < 128 μeql^{-1} high-flow sodium for igneous sites. As these ions are expected to be derived from marine sea salts the differences in magnitudes between geologies is expected to result from the more costal proximity of the Ordovician sites, and the differences in magnitude between events is seen as different proportions of marine derived influence on rainfall.

Figure 8-17 Comparison of regression analyses between sodium and chloride ions and total forestry in 2005 showing a potential "forest effect" on marine ions. Points ringed in grey are from the Luce catchment in the SW of the region, the area of highest sea salt deposition. (Cl/Na units: μeql^{-1})



Despite this variability the relationships of chloride and sodium with forestry are highly statistically significant (P<0.001) in all years. Figure 8-17 shows the "forest effect" for 2005. The relationships on igneous sites are clear and strong: (R^2 ≥0.65; RMSE ≤42 μeql^{-1}). On Ordovician sites there is significant scatter (R^2≤0.27; RMSE >80μeql^{-1}) due to the influence of local factors beyond forestry, such as coastal proximity. The cluster of outlier sites in the grey ring is from the Luce catchment, to the South West of the study area; correlation analysis reveals that both chloride and sodium have a decreasing tendency in a north-easterly direction (Figure 8-18); it is expected therefore that these low forestry areas receive high salt inputs. With the Luce removed the relationship is much stronger (R^2≥0.56; RMSE≤0.54 μeql^{-1}).

Figure 8-18 Spatial correlation of marine ions



A comparison between the Cl:Na ratios for the 2005 and 2006 data (Figure 8-19 and Figure 8-20) shows a chloride bias in the water chemistry is identified for all sites (all ratios > 1) in 2005. A clear "forest effect" is also identified for the Ordovician sites in 2005 and for igneous sites in both years; water leaving afforested sites is richer in chloride than sodium: this leaves an acid anion bias. As a result sea salt scavenging, particularly during significant sea salt events such as that captured in 2005, may be an additional mechanism by which forestry is contributing to the enhanced acidity seen in the "forest effect" on pH in areas beyond those identified by the sulphate-scavenging biased mechanism-down view of the "forest effect". This is particularly important as Larssen and Holme (2006) showed that a "forest effect" on sea salt scavenging could also lead to significant Aluminium pulses which would have an impact on ecology over and above that of the pH trend.

Figure 8-19 Comparison of regression analyses between sodium:chloride ratio and Total Forestry on Ordovician rocks.

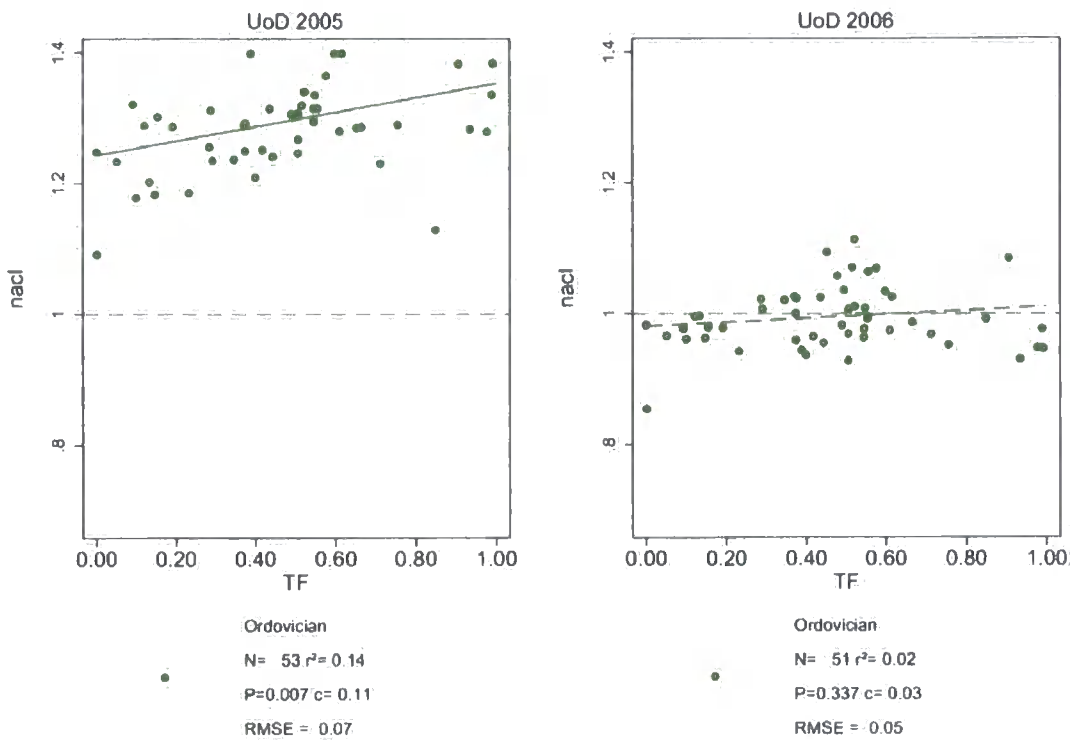
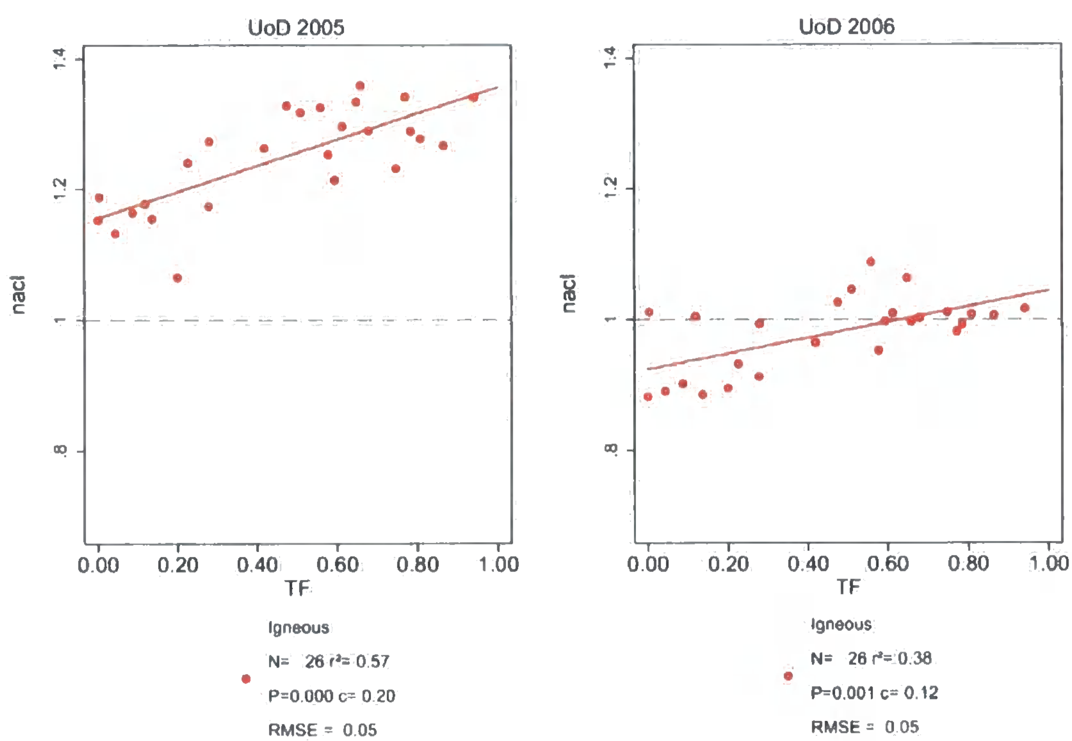


Figure 8-20 Comparison of regression analyses between sodium:chloride ratio and Total Forestry on igneous rocks.

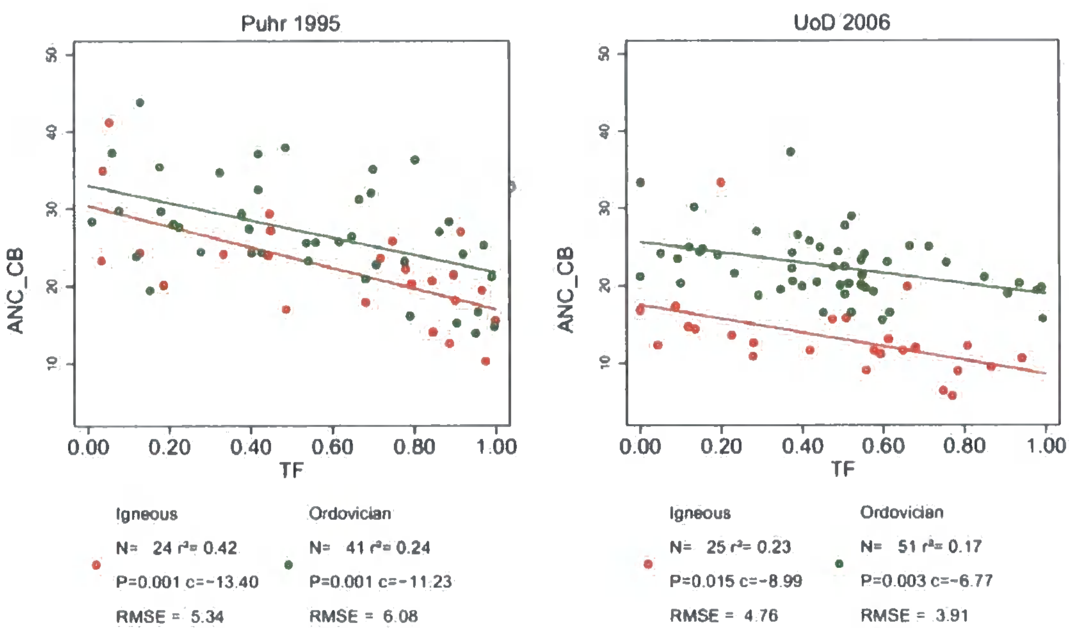


8.6.4 Charge Balance ANC

Charge balance ANC provides a summary of the total acid-base balance of strong ions within a freshwater; it is a measure of *acid sensitivity* areas with a high ANC_{CB} are expected to be well buffered from acid inputs from other sources. The variable is calculated (section 6.2.3b) as the sum of strong acid anions (chloride, sulphate and nitrate) subtracted from the sum of strong base cations (calcium, magnesium, potassium and sodium).

In terms of the trends within these individual variables, there are no significant trends with calcium on either igneous or Ordovician geologies. Relationships with magnesium are also absent at igneous sites, although statistically significant positive relationships are found at Ordovician sites in the 2005 and 2006 surveys. Potassium however shows a significant negative relationship in all three years of data at Ordovician sites, and in 1995 and 2005 at igneous sites (see Table 8-10 and Table 8-11). The relationship with sodium is discussed above as are acid anions, chloride and sulphate: the remaining strong ion; nitrate shows only one significant trend with forestry in 1995 on Ordovician geologies.

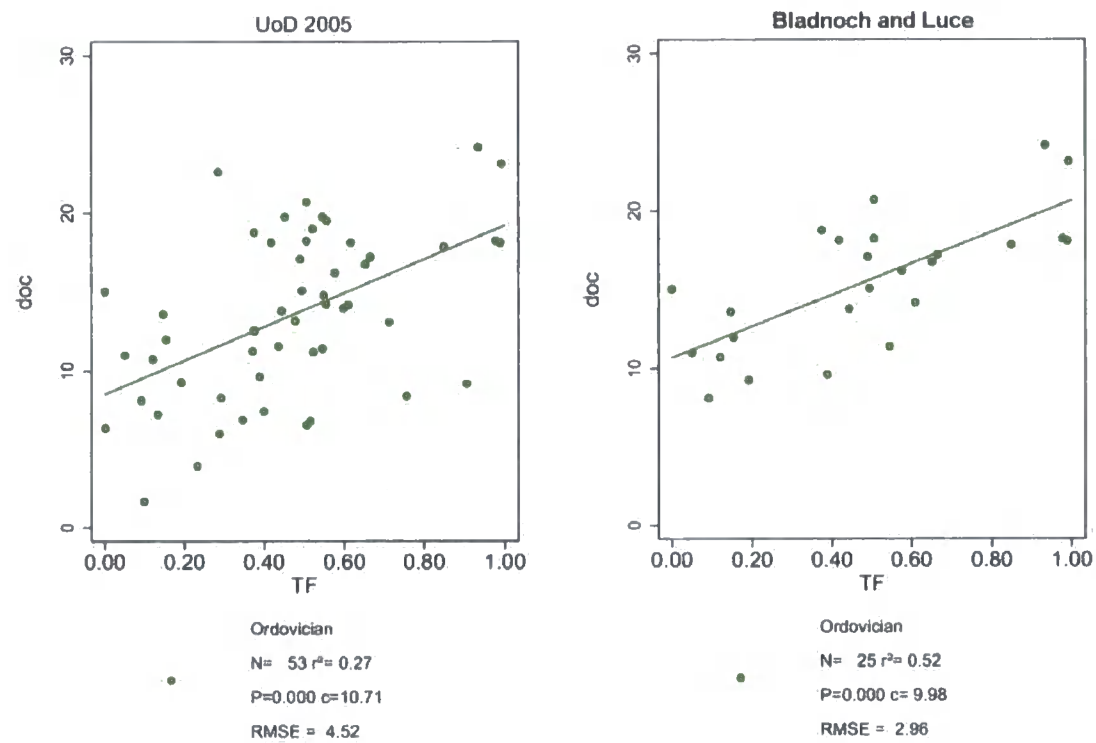
Figure 8-21 Comparison of regression analyses between Charge Balance ANC and Total Forestry (ANC_{CB} units: μeql^{-1})



Charge balance ANC shows a significant ($P<0.01$) negative relationship with forestry in each of the three surveys and on both geologies. This indicates that increasing forest proportion from 0 to 100% would be expected to decrease buffering capacity by $6.58 < c < 13.40$ μeql^{-1} depending on geology and event: the scatter on this is large with RMSE values between $3.91 < RMSE < 6.08$. Nevertheless, the "forest effect" on ANC is repeatedly identified as an impact, suggesting that areas afforested areas below 300m will be more vulnerable to acid inputs.

8.6.5 Dissolved Organic Carbon (DOC)

Figure 8-22 Comparison of regression analyses between DOC and Total Forestry for 2005 both for all Ordovician sites (left) and for a focus on the south-western Bladnoch and Luce catchments (right). (DOC units: mgl^{-1})



In the 2005 event a highly significant (P<0.001) relationship is identified between total forestry and DOC: the regression line suggests that an increase of forest cover from 0 to 100% would lead to an increase of 10.71 mg l^{-1} although there is scatter about this line (RMSE 4.52 mg l^{-1}). If focused only on the lowland catchments of the Bladnoch and the Luce this RMSE is reduced to 2.96 mg l^{-1} and the proportion of the dataset explained increases to R^2 = 0.52.

A relationship between forestry and DOC is interesting as the organic acidity provided by DOC, like sea salt scavenging, provides a potential alternative source of acid anions to explain the "forest effect" on pH in conditions of declining sulphate deposition. It is however less likely to lead to the "forest effect" on fish as whilst the additional DOC may reduce the overall pH, DOC has been shown to form complexes with the toxic forms of aluminium rendering them less damaging to ecology (McCartney *et al.*, 2003). In addition, Monteith *et al.*, 2007 suggest the DOC trends are likely to be a response to recovery from acidification. A "forest effect" on DOC may therefore reflect increasing recovery from acid deposition under sties with greater sulphate inputs as a result of scavenging. Further research would be needed to identify how widespread this "forest effect" on DOC is, what the mechanism behind it is, the extent to which the effect is significant to ecology and fisheries and, as the effect is only detected in the 2005 survey, what types of rainfall events trigger it.

8.6.6 A note on fisheries data

The relationships examined above have focused on water chemistry data rather than ecological data: this is due to the fact that, in practice, very few fisheries sites match existing chemistry sites and, as a result, catchments for which forestry data are available. In the sections below an overview of fisheries-forestry data for two merged time periods is shown: pre-2000 data (1989 and 1995) and post-2000 data (2001, 2003 and 2005) are analysed as two separate groups; potential differences in conditions between years of data must therefore be considered in the interpretation of the data. This grouping is necessary as the majority of available data are from 1995 when fisheries data, collected for Puhr (1997) and stored in the GFT data base, was conducted at the chemistry sites used in this thesis. As a result the pre-2000 data represented below strongly reflects the work of Puhr (1997) and it is not my intention to claim it as my own. There is little post-2000 data available for the catchments studied in this thesis and only 16 sites are available for analysis: the section below is therefore intended to provide a flavour of the ecological "forest effect". The current results are presented below and focus on Ordovician sites with no filtering for proportion of forestry above 300m.

8.6.6a Salmon (Ordovician data only)

A statistically significant ($P<0.01$) "forest effect" is shown in the 1989 and 1995 data (Puhr, 1997) for both salmon fry (s0) and parr (s1); only the relationship with salmon parr is significant ($P< 0.05$) in the post-2000 data. Without more data it is difficult to tell the extent to which the contemporary data are different from, or simply a subset of, the trend seen in the 1995 data. Either way it appears that sites with absent salmon appear to be present in areas with high levels of forestry at both of the life stages in both pre and post 2000 datasets: a situation made probable as the analysis above suggests the "forest effect" continues to contribute to an increase in freshwater acidity. Both datasets for fry and parr suggest that problems for salmon increase when the catchment proportion is over 50%; but, again, further robust analysis is required to investigate these impacts.

Figure 8-23 Comparison of regression analyses between salmon fry (0+ years in age) and Total Forestry (s0 units: log(counts))

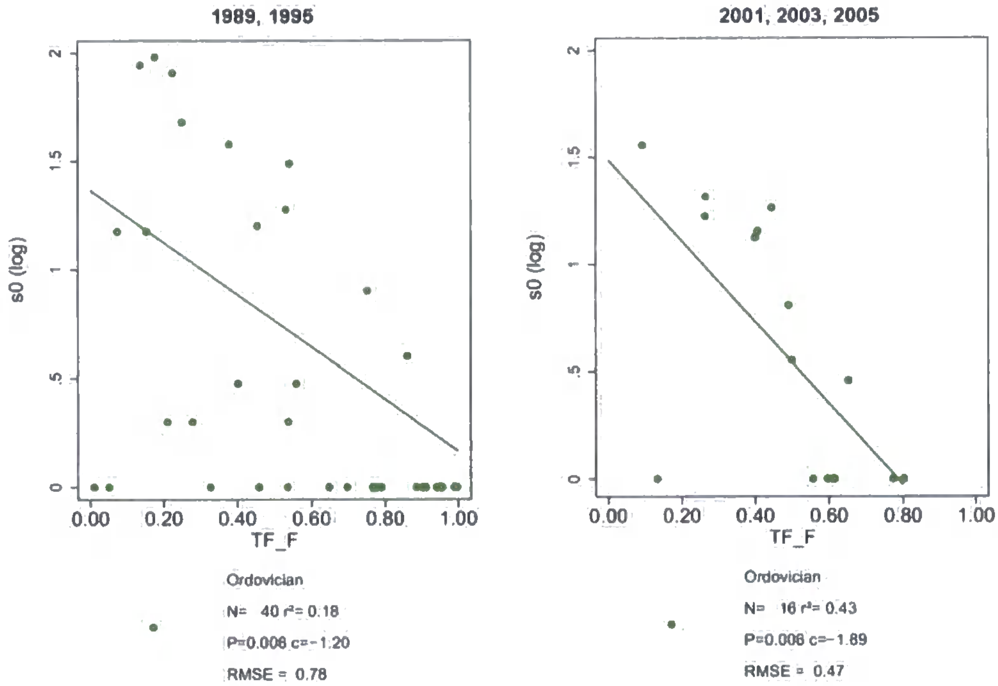
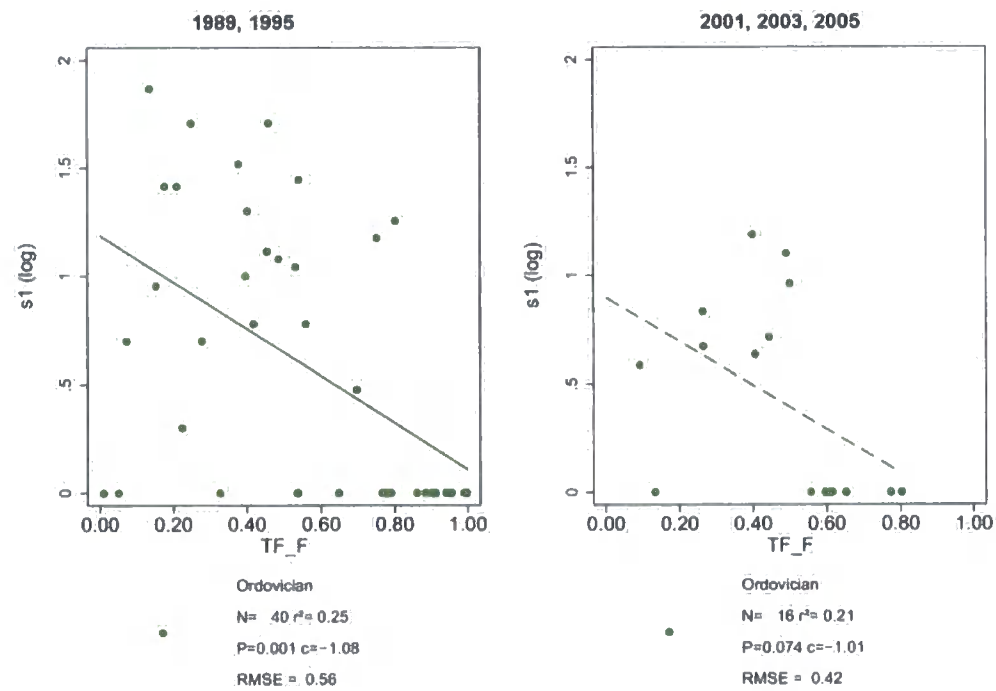


Figure 8-24 Comparison of regression analyses between salmon parr (1+ years in age) and Total Forestry (s1 units: log(counts))



8.6.6b Trout (Ordovician data only)

Trout data also show negative trends in the pre-2000 data, although these trends are less statistically significant; significant at P<0.05 rather than P<0.01. No statistically significant (at P<0.05) trends are identified in the post-2000 data: the lack of data makes interpretation difficult; following the fisheries trusts comments (Chapter 7) that there were few sites where there are no trout present it is possible that the post 2000 trout parr (t1) graph shows the potential for ecological recovery however more robust analysis is required.

Figure 8-25 Comparison of regression analyses between trout fry (0+ years in age) and Total Forestry (t0 units: log(counts))

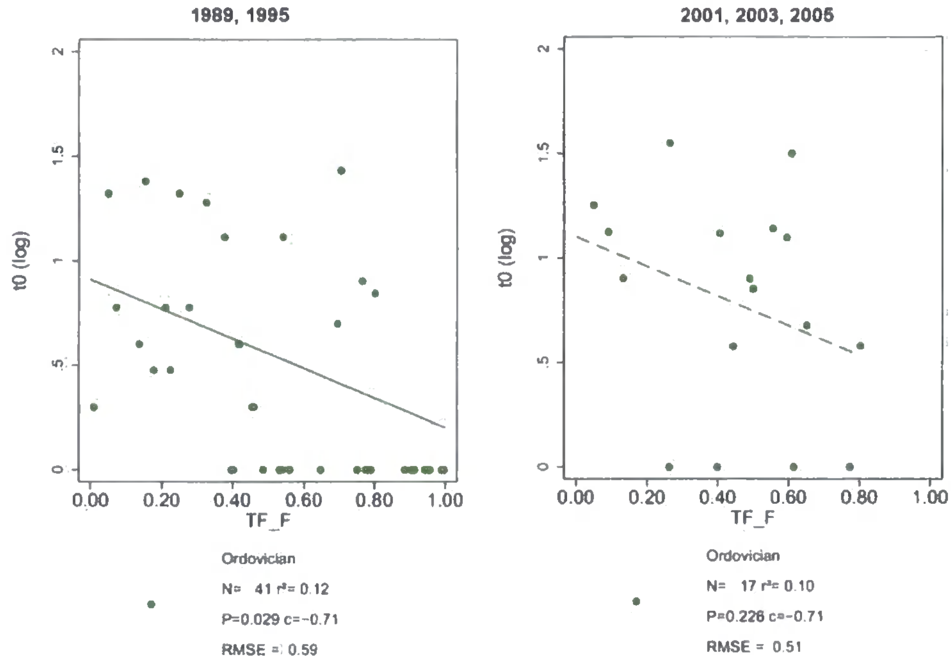
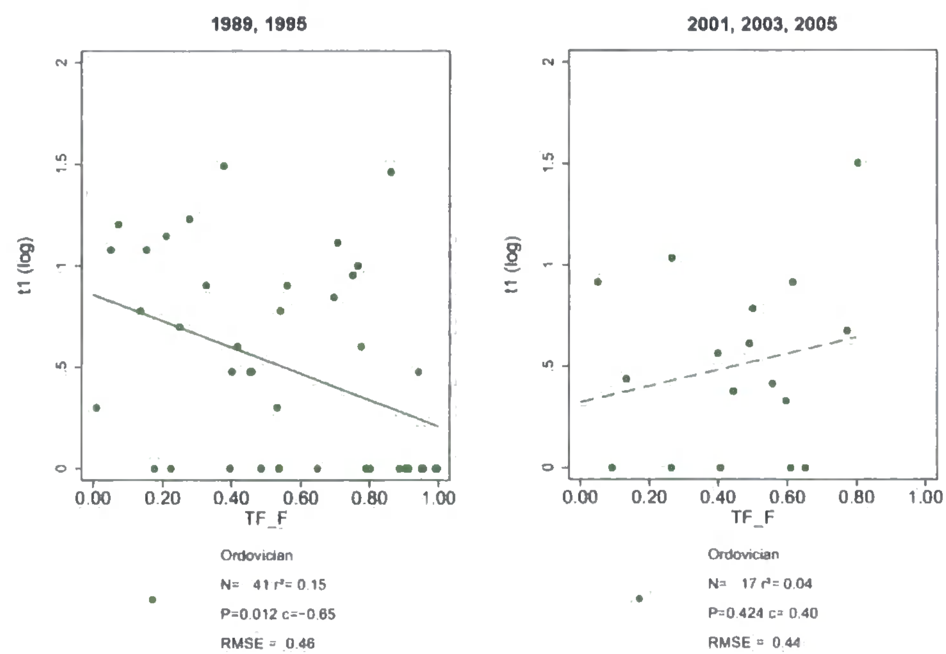


Figure 8-26 Comparison of regression analyses between trout parr (1+ years in age) and Total Forestry (t1 units: log(counts))



8.6.6c Summary

A "forest effect" on fisheries is shown to be possible, and is identified as significant negative trends between both salmon and trout in pre-2000 data (following Puhr, 1997): it is impossible to interpret robustly whether this "forest effect" continues due to lack of data; however, the impact on chemistry data and the continued concerns of the GFT suggest that this may be the case. Further research is required to make best use of fisheries data; the extraction of forestry by fish-site catchment would be a relatively simple and informative further extension to this project and contribute to better available knowledge on the ecological "forest effect".

8.7 Multiple regression

The analysis in the previous section subset data as a means to control for the influences of geology; the aim was to keep interpretation simple and allow indications of the significance of each effect to be shown in real units. In this section a multiple regression approach is applied to all the available data to look at many variables at once in an attempt to provide insight into the relative role played by forestry and other catchment variables. An additive stepwise approach is used; variables are added to the model in order of the greatest contribution they play to the overall explanation of the data that they contribute (R^2). This is performed separately for each survey and the completed model is presented in the tables below. The non-forestry catchment variables included are: total S deposition, rainfall, altitudinal range, maximum altitude, the proportion of igneous and Ordovician geology and the northing and easting (see section 8.3.3). The additional variables minimum altitude and mean altitude were automatically removed by the regression approach due to collinearity; Silurian proportion is represented by negative relationships with the other two geology variables.

Only water chemistry variables where a "forest effect" was identified in the previous section are discussed below: as a result SEPA long-term records are only analysed in the section regarding pH.

8.7.1a The stepwise methodology

The tables below show the *additional* proportion of the model explained by each variable during the stepwise approach. An additive approach was preferred whereby all variables are considered for inclusion and the one A reflexive approach was taken by which a number of models were investigated starting with high levels of statistical significance and increasingly reducing the stringency of the criteria; Table 8-12 shows a key to these. The models explored began with additive models using, in turn, significance thresholds of P<0.001, P< 0.01 and P<0.05. The process was after both i) a model significant at a minimum of P<0.05 and ii) a model significant at a minimum of P<0.05 *and* including TF as a variable were identified. The additive approach selected variable for inclusion within the regression model if that variable a) was statistically significant at the chosen P value and b) offered the greatest increase to R^2 compared with the other potential values. If no models were identified using an additive approach the same three P values were applied to a subtractive approach: in this case, all variables were added to the model and the variable that offered the least significant P value was removed providing that P value was above the selected significance threshold.

The tables below show the proportional contribution to the overall R^2 of the inclusion/exclusion of each variable; the statistical significance of these values is shown: the legend for the interpretation of all tables is presented in Table 8-12.

Table 8-12 Legend for all tables

Significance	Model	Variable
P<0.001	†††	***
P<0.01	††	**
P<0.05	†	*

Trend direction		
Positive	+	
Negative	-	

Variable Codes	
Total Forestry	TF
Igneous %	Ign
Ordovician %	Ord
Easting	X
Northing	Y
Rainfall	rain
Maximum Altitude	Alt
Altitudinal Range	AltR
Total S Deposition	SO4

Variable list in order included/dropped
RMSE in units of variable (see Table 8-1)
All other variables are proportion of overall variation explained.

8.7.1b pH

Forestry is included as an explanatory variable for pH in all high-flow surveys; the models themselves, and the contribution of forestry within these models, are highly statistically significant (P<0.001). The proportion of the variation within the dataset explained by a "forest effect" is shown to be between 6 and 19% for high-flow surveys and between 11 and 25% for median-flow surveys. In the high-flow surveys the lower contemporary values suggest that the "forest effect" on high flows may have decreased with time. The median-flow "forest effect" is, however, if anything, stronger in contemporary samples. The remaining 40-50% of the dataset explained by the models, is often related to the proportion of igneous geology (≈11-15% in high-flow data and 1989/1995 long-term data), total S deposition (24-31% in long-term 2003/2005 data) and an east or north-easterly trend (12-32% in all surveys). This is expected as the proportion of igneous geology will provide a control on acid sensitivity, and the east north easterly direction of increasing pH may reflect a decreasing sea salt input. The strong relationship with lower pH in areas of high total sulphur in 2001 and 2003 is also likely to reflect this northerly trend; total S deposition and northing correlate with an r of 0.6 (see Figure 8-3): it is thus more likely a problem of collinearity rather than suggesting total S deposition leads to a high pH.

Table 8-13 pH High-flow surveys: multiple regression

	Puhr 1995	Durham 2005	Durham 2006
	Additive †††	Additive †††	Additive †††
	- TF 0.19***	- ign 0.31***	- ign 0.26***
	- Ign 0.15***	+ X 0.12***	+ Y 0.14***
	+ X 0.34***	- TF 0.09***	- TF 0.06***
			+ X 0.06***
R^2	0.68	0.55	0.52
RMSE	0.35	0.55	0.54
N	93	114	113

Table 8-14 pH SEPA long-term: multiple regression

Contributions to overall R^2 in order added to model					
	SEPA 1989	SEPA 1995	SEPA 2001	SEPA 2003	SEPA 2005
	No "forest effect" Additive ††	Subtractive †	Additive †††	Additive †††	Additive ††
	-Ign 0.35**	-Ign 0.12**	+X 0.29***	-TF 0.25***	-TF 0.20***
		+X 0.11**	-SO4 0.31***	-SO4 0.24***	+X 0.18***
	Additive †	-TF 0.13**	-TF 0.15***	+X 0.18***	+Y 0.14**
	-Ign 0.35***	+Y 0.14*			-Ign 0.11**
	-Ord 0.13**				
	-TF 0.11*				
Model Statistics					
R^2	0.35: Model 1 (†) 0.58: Model 2 (††)	0.51	0.75	0.67	0.62
RMSE	0.45: Model 1 (†) 0.38: Model 2 (††)	0.38	0.23	0.31	0.33
N	24	30	36	43	40

8.7.1c Sulphate

Table 8-15 Raw sulphate: multiple regression

	Puhr 1995	Durham 2005	Durham 2006
	Additive †††	Additive †††	Additive †††
	- SO4 0.37***	- Y 0.30***	- Y 0.30***
	+ TF 0.22***	+ TF 0.11***	+ TF 0.17***
	+ X 0.15***	- ign 0.04***	+ X 0.07***
		+ X 0.13***	- ign 0.08***
R^2	0.74	0.58	0.62
RMSE	4.26	2.80	3.4
N	93	114	113

Multiple regression analysis confirms the "forest effect" on sulphate; both the model and the forest contribution are highly significant (P<0.001) and the forestry component contributes to the explanation of 11-22% of the variation within the dataset depending on the event. The remaining c.50% of the data explained by the model is described by a southerly trend of increasing sulphate reflecting the comparative low sulphate concentrations in the upper Dee, particularly in the Carsphairn system.

8.7.1d Critical Load Exceedance

Table 8-16 Critical Loads Exceedance: multiple regression

	Puhr 1995		Durham 2005		Durham 2006	
	No "forest effect" Additive †††		Additive †		No "forest effect" Additive †††	
	+ SO4	0.22***	+ SO4	0.46***	+ rain	0.39$^{n/s}$
	- AltR	0.12***	+ ign	0.11***	+ SO4	0.07***
	- X	0.14***	- X	0.08***	+ ign	0.05***
			+ TF	**0.02***	- X	0.05***
R^2	0.48		0.67		0.56	
RMSE	1.07		0.63		0.89	
N	93		114		113	

Critical Loads exceedance was shown to have no relation with forestry 1995 or 2006 even with subtractive approach at P<0.05; the models shown are instead those significant at P<0.001 following the additive method. In 2005 forestry is shown to have a significant relationship with an additive model at P<0.05 however TF only explains 0.02 of the variation. The large proportions of the dataset explained by total S deposition (R^2 = 0.22 and 0.46 in 1995 and 2005 respectively) and rainfall (R^2=0.39 in 2006) modified by igneous geology and a westerly direction are difficult to interpret due to multicollinearity between the rain and total S datasets (r=0.576 see Figure 8-3). However, it is clear that the pattern of Critical Loads exceedance matches well with a general trend of high values in the wetter areas with greater total sulphur deposition: the western Cree, eastern Dee and upper Fleet and Palnure (see Figure 6-18).

8.7.1e Marine Ions

8.7.1e(i) Marine Ions (chloride)

Table 8-17 Chloride: Multiple regression

	Puhr 1995		Durham 2005		Durham 2006	
	Additive †††		Additive †††		Additive †††	
	- SO4	0.58***	- Alt	0.48***	- Alt	0.50*
	+ TF	**0.07*****	- X	0.29***	- X	0.10***
			+ TF	**0.08*****	**+ TF**	**0.07*****
					- Y	0.06***
					- SO4	0.03**
R^2	0.65		0.84		0.79	
RMSE	32.60		52.09		34.63	
N	93		114		113	

Marine ions, represented above by chloride, follow the inverse trend to Critical Loads exceedances; they show strong relationships in a South Westerly direction identified by an inverse relationship with total sulphur deposition, altitude, easting and northing which explains 55-75% of the variation within the dataset. The "forest effect" explains an additional 7-8% and is highly statistically significant (P<0.001).

8.7.1e(ii) Marine ions (Cl:Na ratio)

Table 8-18 Chloride:Sodium ratio : Multiple regression

	Puhr 1995	Durham 2005	Durham 2006
	No "forest effect" Additive †††	Additive †††	No "forest effect" Additive †††
	-SO4 0.23***	**+ TF 0.21*** **	- SO4 0.9***
		- Alt 0.08**	
R^2	0.23	0.29	0.9
RMSE	0.07	0.07	0.09
N	93	114	113

The "forest effect" is, of the variables investigated, identified as the major component influencing the chloride:sodium ratio in 2005; 21% of the variation within the dataset is explained and both the model and the variable's inclusion are supported by a high statistical significance (P<0.001). Altitude provides an additional 8% explanation of the variance with the lowland study sites showing higher chloride bias: this is expected to reflect coastal proximity. No "forest effect" is identified in either 1995 or 2006; instead a relationship with total sulphur deposition is shown (R^2 = 0.23 in 1995; 0.9 in 2006); this is likely to reflect South Westerly trend interpreted for the chloride relationship above.

8.7.1f Charge Balance ANC

Table 8-19 Charge Balance ANC : Multiple regression

	Puhr 1995	Durham 2005	Durham 2006
	Additive †††	Additive †††	No "forest effect" Additive †††
	-TF 0.25* **	- ign 0.27***	- rain 0.32***
		- ord 0.09***	+ Y 0.17***
		- TF 0.09* **	Additive ††
			- rain 0.32***
			+ Y 0.17***
			- TF 0.04 **
R^2	0.25	0.45	0.49: Model 1 (†††) 0.53: Model 2 (††)
RMSE	6.36	4.94	5.55: Model 1 (†††) 5.36: Model 2 (††)
N	93	114	113

The "forest effect" on charge balance ANC explained is statistically significant at P<0.001 in both 1995 and 2005 and at P<0.01 in 2006. The proportion of the variation in the dataset explained is lower in contemporary samples (0.09 and 0.04 in 2005 and 2006 respectively) than in the 1995 sample (R^2 = 0.25); this is likely to reflect the decrease in total sulphur deposition. The 1995 model can be improved (at P<0.05) to an R^2 of 0.42 by including easting (positive) and the proportion of igneous (negative) in 1995 (all contributions significant at P<0.001). This and the relationships with non-forestry variables in the 2005 and 2006 data indicate a strong connection between high ANC and the non-igneous areas: rainfall, identified as a factor in 2006, has a strong correlation (r = 0.7; see Figure 8-3) with the proportion of igneous rocks. Again, multicollinearity differentiation between these factors makes interpretation difficult.

8.7.1g Dissolved Organic Carbon

Table 8-20 DOC : Multiple regression

	Durham 2005		Durham 2006	
	No "forest effect" Additive †††		Additive †††	
	- Alt	0.17***	- X	0.27***
	+ Ord	0.10***	**+ TF**	**0.07****
R^2	0.27		0.34	
RMSE	5.04		4.4	
N	114		113	

The relationship with DOC shows a "forest effect" significant at P<0.01 in 2006 explaining 7% of the variation within the dataset. No relationship is found with Total Forestry in 2005: this is in contrast to the statistically significant trend found in the simple regression analysis in areas below 300m (8.6.5). Instead, high DOC values are seen to be related to lower altitudes and Ordovician geologies; in 2006, 27% of the variation in the data are driven by a westerly tendency. To examine this issue further the 2005 data were restricted to the Bladnoch and Luce: a model significant at P<0.001 that used TF alone was shown to have an R^2 of 0.47*** with a positive relationship with forestry based on 29 points. It is possible that the peaty soils in these catchments contribute to this effect but further research would be required to investigate this.

8.8 Discussion

8.8.1 The "Forest effect"

Studies that have taken a regression based approach to the relationship between forestry and acidification using a spatially distributed sample of sites of different forest cover proportions include Wright and Henriksen (1979), Ormerod *et al.* (1989) and Puhr *et al.* (2000). Of these, Wright and Henriksen (1979) found no significant relationship between forest cover and pH whilst both Ormerod *et al.*, 1989 and Puhr *et al.* (2000) identified statistically significant forest effects. Puhr (1997) argues that the lack of "forest effect" identified by Wright and Henriksen (1979) may have resulted from the fact that the forested areas were young and not reached canopy closure at the time of survey, a fact he justifies drawing on Forestry Commission planting data. In addition, Wright and Henriksen (1979) did not sub-sample by geology and their regression-based work focuses on lakes rather than rivers. It is likely that it is a combination of these factors masked an identification of a "forest effect" using this methodology.

Table 8-21 Summary of regression-based approaches to identifying the "forest effect".

Data source		Geology	N	c	R^2
		Lakes			
Wright and Henriksen (1979)	Galloway	No separation	50	n/s	n/s
		Streams			
Ormerod *et al.* (1989)	Llyn Briane (Wales) Annual Mean	$CaCO_3$ <10mg	68	-0.6***	0.16
		$CaCO_3$ 10-15mg	23	-1.0***	0.44
		$CaCO_3$ >15mg	20	-0.6***	0.51
SEPA 1989	Galloway	Ordovician	15	-1.86*	0.33
SEPA 1995		Ordovician	21	-1.32*	0.25
SEPA 2001	4 Sample Annual Mean	Ordovician	26	n/s	n/s
SEPA 2003		Ordovician	28	-1.20**	0.30
SEPA 2005		Ordovician	28	-1.81***	0.39
Puhr 1995 (unstratified by <300m)	Galloway	Igneous	29	-0.34**	0.30
		Ordovician	50	-0.68***	0.21
	High flow sample	Silurian	14	-2.07**	0.45
Durham 2005 (unstratified by <300m)	Galloway	Igneous	28	-0.49**	0.24
		Ordovician	73	-0.82*	0.09
	High flow sample	Silurian	13	n/s	n/s
Durham 2006 (unstratified by <300m)		Igneous	28	-0.73***	0.39
		Ordovician	71	n/s	n/s
		Silurian	14	n/s	n/s

Grey = New in this thesis; White = from other authors
(NB Puhr 1995 data were reprocessed in this thesis, but the strength of relationships will be similar between SWAIH and TF, whilst the detail of the regressions themselves will differ)

The results from Puhr *et al.* (2000) are not presented here as the data used in their paper has already been included in the analyses above (as the Puhr 1995 dataset), the only difference being Puhr *et al.* (2000)'s definition of forest cover was based on SWAIH (Puhr's (1997) structurally weighted afforestation index of height, see 6.5.3d) rather than Total Forestry (TF). Table 8-21 summarises the findings of regression-based approaches for identifying the "forest effect" and its relation to pH. It shows that for Ordovician and igneous rocks, the contemporary (2005/6) findings of this thesis, a "forest effect" impact on pH between -0.49 and -0.82, fit well alongside those of both the Puhr dataset and the results of Ormerod *et al.* (1989). The fit with Puhr's values is to be expected as many of the same rivers are sampled; however, there is a notable lack of significant pH trends on Silurian sites in 2005 and 2006, and on Ordovician sites in 2006. These trends were present in both the Puhr dataset and the long-term records in between these years. Whilst this change may reflect an amelioration of the "forest effect" in high-flow surveys, potentially as a response to decreasing sulphate deposition (NEGTAP, 2001), it may also reflect the sensitivity of the regional sampling methodology to the individual conditions of the storm event (discussed below). This is a by product of the regional-scale approach taken in this thesis. The regional approach focuses sampling on attaining enough spatial variety to allow environmental management hypotheses to be explored directly with statistical tests whilst controlling for catchment factors external to the "forest effect" such as differences between acid inputs, base cation buffering, rainfall and altitude. However, the feat of activating six teams of individuals to survey 117 sites during one storm event limits the number of times such surveys can be performed. Whilst it is possible to compare storm events (Appendix C) the differences between individual surveys will vary due to a range of additional factors, including: impacts of climate change on weather systems (Wright *et al.*, 2006; Wright, 2008); impacts of the NAO on nitrate (Monteith *et al.*, 2000) and sea salt (Hindar *et al.*, 2004; Laudon, 2008) and acid pulse episodes (Laudon, 2008; Kroglund *et al.*, 2008). These factors encourage careful interpretation of differences between individual surveys.

The "forest effect" on Ordovician rocks using the 'median-flow' pH from the long-term surveys is more clear, in the order of $c \geq -1.2$ pH; this finding is considerably higher than that of Ormerod *et al* (1989) who showed a maximum coefficient of $c = -1$ pH unit. Differences in local geology and soils may explain this, as are differences in survey methodology: the key message is the fact that despite the published reduction in sulphate deposition (e.g. NEGTAP, 2001) a "forest effect" is shown to be present by regional scale regression analyses of this type.

It is also important to note the variability in the data present in all the regression approaches, with relatively small proportions of the overall variation in the dataset explained in all studies (Table 8-21). R^2 values are at maximum ≈0.5 and for many of the surveys ≤ 0.3. As demonstrated in section 3.2.4a, this scatter was enough for the Forestry Commission to argue that "extrapolating the data for the purpose of setting guidelines would be invalid" (Nisbet, 1990b). Whilst it is valid to consider carefully how this knowledge is input into the decision making process, it is clear that a "forest effect" continues to exist, answering the Forestry Commissions previous doubts of whether or not the effect "can be transferred to a point in the future where acid deposition levels are expected to be lower" (Nisbet, 1990b). The "forest effect" is still there; the extent to which it can be considered responsible for fisheries decline however, is discussed in the section 8.8.3.

The findings of the regression-based approaches reinforce the paired-catchment studies dismissed by the Forestry Commission in Nisbet (1990). As discussed in Chapter 3, the Forestry Commission had argued that the "basic assumption" of the comparability of paired catchments was flawed. Whilst this argument can never be totally dismissed, the detection of regional-scale "forest effects" encourages greater confidence in the interpretations of Harriman and Morrison (1981, 1982), Stoner *et al.*

(1984), Stoner and Gee (1985), Ormerod and Edwards (1985), Reynolds *et al.* (1986) and Harriman *et al.* (1987) who all also identified decreases in pH related to afforestation (see Table 3-2 for a summary of these effects) using paired-catchment approaches. The identified "forest effect" on pH are further reinforced by the long-term studies with Lees (1993) and Langan and Hirst (2003) who show a "forest effect" using long-term Loch Dee data; the afforested Green burn shows less signs of recovery than the moorland Dargall Lane. As explained in Chapter 4 the lack of an identified "forest effect" by Nisbet *et al.* (1995) using the same data as Lees (1993) may reflect the youth of the trees in 1995 (see Figure 4-4) which meant that the ability to detect trends could be significantly impacted by the way the data are processed prior to interpretation. The following chapter investigates the Loch Dee data further to update the work of Langan and Hirst (2003) by showing trends to 2005.

8.8.2 The "Forest effect" mechanism

As discussed in previous chapters the only mechanism agreed by the Forestry Commission and the AWRG as significant enough to explain the "forest effect" and to be included in policy was sulphate scavenging. Experimental studies performed within the region (Harriman and Morrison, 1982; Puhr *et al.*, 2000; Harriman *et al.*, 2003) have presented evidence in support of a sulphate scavenging effect (Mayer and Ulrich, 1974; Fowler, 1989). Of these, Puhr *et al.* (2000) identifies a statistically significant positive correlation at a regional scale. The work in this chapter expands on this to show that statistically significant positive trends between sulphate and forestry continue to be found 10 years after the last regional survey (Figure 8-14). It is, however, significant to note that the strength of the relationships shows signs of having decreased (c=15.63*** in 1995 but c=4.63** and 8.43*** in 2005 and 2006 respectively (Ordovician rocks, unfiltered) see also Figure 8-14) This overall trend in decreasing in freshwater sulphate is consistent with the decreases in freshwater sulphate at both national (Evans and Monteith, 2001) and international (Evans *et al.*, 2001) scales. In a context of approximately 70% less sulphate available for scavenging (NEGTAP, 2001) the detected decrease in the "forest effect" on sulphate is expected. It is important to note that, whilst the y-intercept is 10 μeql^{-1} lower in 2006 than 1995 and the coefficient in 2006 is half that in 1995, the "forest effect" is still in operation: the coefficient remains positive and significant at $P<0.01$ in both 2005 and 2006. Very few other studies have taken a regression approach to focus on the "forest effect" on sulphate in the UK or internationally and so there is little data to compare it with beyond that of Puhr *et al.* (2000).

If the sulphate-scavenging effect is indeed in decline it is necessary to consider what additional factors may be contributing to the "forest effect" on pH identified in both the high flow event of 2005, and the most recent long-term survey data (both 2003 and 2005).

The most notable alternative mechanism that may offer an explanation are the trends identified in sea salt sodium and chloride ions which are greater in contemporary surveys (c=68.28*** in 1995, c=113.55*** and 123.08*** in 2005 and 2006 respectively (sodium; Ordovician rocks, unfiltered) see Figures 8-17 and 8-19). This enhanced capture of sea salts is expected, following a similar scavenging mechanism to that for sulphate (Fowler, 1989) and seen demonstrated in numerous other studies (Wright and Henriksen, 1979; Stoner and Gee, 1985; Welsh and Burns, 1987; Ormerod 1989). However, unlike anthropogenic sulphate, sea salt trends fluctuate with climatic forcing (Hindar *et al.*, 2004; Wright *et al.*, 2006; Laudon, 2008) rather than declining in response to decreased pollutant sulphate output. As a result, they are capable of being as strong now as in the past, and with climate change have the potential to increase in significance (Wright *et al.*, 2006).

The evidence for a relationship between Cl:Na ratio and forest cover shown in Figures 8-17, 8-19 and 8-20 is particularly significant and suggests that chloride ions passing through the system will be available to displace H^+ and Al^{n+} anions. The sea salt threat to freshwaters has a been widely discussed in the academic literature (Welsh and Burns, 1987; Heath *et al.*, 1992; Harriman *et al.* al, 1995; Neal and Kirchner, 2000; Davies *et al.*, 2005; Laudon *et al.*, 2008), although there are very few studies that focus specifically on the role of a "forest effect" in exacerbating these events (Cf. Harriman *et al.*, 1995; Larssen and Holme, 2006). Harriman et al (1995) is one exception and notes similar impacts in high sulphate deposition catchments with moderate sea salt impacts and indicate that "*for the same salt episode and sampling date the 90% forested catchment [(compared with a 30% afforested one)] had the highest chlorine gradient ... enhancement of acidity and labile aluminium and also the highest base cation release*". Harriman *et al.* (1995) did not however investigate the "forest effect" on sea salt scavenging in catchments in areas of low sulphur deposition catchments; only moorland sites were studied, and it was concluded that sea salt inputs of chloride were matched by sodium ions resulting in very little impact on acidity or aluminium production (Harriman *et al.*, 1995). The work of Larssen and Holme (2006) updates this however; they perform similar comparisons in Norway using paired spruce/birch catchments across a range of deposition conditions. Their work indicates that "mobilization of acidic cations (H^+ and Al^{n+}) dominated in spruce afforested catchments, while the adjacent birch catchments to a large extent release base cations, in particular Ca^{2+}" (Larssen and Holme, 2006). This effect is demonstrated even in the low sulphate deposition sites in northern Norway (Larssen and Holme, 2006), suggesting a potential "forest effect" even in sites where sulphate-scavenging is no longer a risk. The findings of this thesis fit well with these other studies by providing a spatial sample of sites within a low deposition area to reinforce the view that a "forest effect" of exacerbated sea salt conditions can occur. With decreasing sulphate deposition it is possible that this effect may take over as a more significant "forest effect" than the sulphate-scavenging mechanism of the FWGS (FC, 2003). Furthermore, sea salt impacts are particularly significant in the longer term, as sea salt events will be influenced both by natural fluctuations such as the NAO (Hindar *et al.*, 2004) but also by long-term increases in temperature precipitation and storminess that result from climate change (Wright *et al.*, 2006).

8.8.3 The ecological significance of the "forest effect"

The fisheries data presented in section 8.6.6 show both the results of Puhr *et al.* (2000; in a reprocessing of their original data) and more contemporary fish numbers for of the few sites where water quality monitoring and GFT survey sites coincide. Whilst the "forest effect" on fish is notable and statistically significant for all fish classes in Puhr's 1995 data, the same is only the case for the most vulnerable salmon fry class in the 2001-2005 data. It is difficult, due to the scarcity of contemporary data (17 points from three different years), to draw robust conclusions from any of these regression relationships; the weakness of relationships may simply reflect the low number of samples. This noted, there is little evidence to contradict a "forest effect". The trend direction on both trout fry and adult salmon is negative, albeit non-significant and no large numbers of fish are shown in the high forest cover percentages (> 60% for trout fry, > 70% for adult salmon). This is not the case for adult trout, however, and high counts are shown even in areas of 80% forestry, and a positive trend that is *not* significant at $P<0.05$ is shown. It is therefore possible that this may be a sign that the adult trout populations (the least acid sensitive species/age-class) are in a better condition than when surveyed in 1995.

Gee and Stoner (1988) also failed to identify statistically significant trends with fish (trout) numbers. They however argued for a "forest effect" stressing that although these relationships were lacking there were strong correlations between forestry and increased pH and aluminium, and between these water chemistry variables and fish mortality. The same argument can be made in this study as there is research to support the view that low pH (<5) impacts the salt balance in fish (Muniz *et al.*, 1984;

Sutcliffe and Carrick, 1973; McWilliams, 1982), that hatching enzymes are affected below pH 4.5 (Haya and Waywood, 1981) and that aluminium is most soluble at around pH 5 (Muniz and Levistad, 1980), which Harriman (1988) summarise as a critical pH of 5.5. As a result the existence of a "forest effect" that shows areas under forestry being more commonly under pH 5.5 on both igneous and Ordovician rocks (Figure 8-11) would suggest that an ecological "forest effect" on fish might be expected.

However, to gain a better understanding of a "forest effect" on ecology aluminium data would be required. With aluminium data, ecology data and catchment forest structural information it would be possible to test the hypothesis that the "forest effect" on ecology is related to an increase aluminium in afforested freshwaters (as indicated by Puhr *et al.*, 2000). The focus of data collection and chemical analysis within this study was on variables used within the *Forest and Water Guidelines* and aluminium analysis was not included (and prohibitively time consuming and expensive to perform). It was beyond the scope of this study to test all the possible hypotheses that link forests to ecological damage. Toxic aluminium is, however, expected to be the greatest cause of fish death (Muniz and Levistad, 1980), and both Puhr (2000) and Ormerod *et al.* (1989) found statistically significant relationships between forest cover and aluminium concentrations to match the significant trends in pH they identified. Whilst it is recognised that decreasing pH increases aluminium solubility (Muniz and Levistad, 1980) this is complicated by the role of DOC which forms complexes with the toxic forms of aluminium modifying the threat to ecology (Ribbens *et al.*,1995; Dijkstra, 2003). As a result, whilst the continuation of the "forest effect" on pH may well suggest an ecological impact, and matches well with the local knowledge around the issues, further scientific study focusing on aluminium would help to more rigorously assess any impacts on ecology. That said, it must be recognised that i) any interpretation of an ecological impact on fish stocks based on chemistry alone is premature given the complex factors beyond simple chemical status that drive fish mobility ii) that water quality samples measure upstream pollution, but it is the water downstream through which the fish swims and iii) that fish stocks are not the only ecological indicators; other more sensitive species such as invertebrates and diatoms will be at risk first. As a result, considerable paired ecological-chemical work would be required to control for all these factors when investigating the ecological "forest effect".

8.9 Conclusion

There is evidence for a continued "forest effect" on freshwater chemistry in Galloway. It appears as relationships showing a decrease in pH, charge balance ANC and increase in sulphate and marine ions in river water with increasing proportion of forestry: most of these relationships show significant scatter and explain small proportions of the total variation in the variable (between 6-25% for pH) suggesting that the "forest effect" is a subtle exacerbation influenced by local variations; however, the relationships are statistically significant at $P<0.05$ and found repeatedly in multiple years of high-flow data and on median flow pH indicating that the effect has continued potential for real ecological implications.

Although forest scavenging of sulphate has reduced with declining emissions, a "forest effect" on sulphate continues even below 300m. Whilst the exploration of mechanisms for the "forest effect" in addition to sulphate scavenging is beyond the scope of this current project, the increased bias towards chloride rather than sodium in sea salt ions making it to freshwaters has been identified as potential sources of acid anions that may contribute to acidification under conditions of declining sulphate; further research is necessary to understand these mechanisms. Significant annual and inter-event variability has also been shown. This will need to be taken into consideration whenever any single water quality sample, even a "worst condition" high flow sample, is used for the purposes of decision making. Both the 2005 and 2006 events were high flow: their chemistry, severity and responses to the "forest effect" were different in many ways (e.g. Figure 8-11).

The "forest effect" was clearly identified in sites with little or no forestry above 300m; furthermore, no significant relationship was identified between Critical Loads exceedance and forestry suggesting that it is an inappropriate tool for the purpose of identifying areas suffering from a "forest effect". This suggests that both the 300m rule and the Critical Loads model are factors that have prevented the *Forest and Water Guidelines* addressing the areas in which the "forest effect" has the potential to pose a risk. In addition, the *Forest and Water Guidelines* have prevented the transfer of local knowledge into forest management practice. In Chapters 5 and 7 it was shown that the FC practice had access to local GFT knowledge and data and that the local FC themselves had an implicit recognition of a wider "forest effect" (4.3.3). Nonetheless, it was shown that Guidelines are the focus of forest management practice and take precedent over external influences (5.3.1b). This chapter argues that Best Available Knowledge surrounding the "forest effect" supports the local-knowledge-based views of a wider "forest effect". By focussing forest management on areas of risk in contrast to this local knowledge (and a wider "forest effect") the *Forest and Water Guidelines* become a factor that hampers the ability of Forestry Commission practice to include Best Available Knowledge.

Chapter 9 : Spatial and temporal trends in forestry and water quality

9.1 Introduction

9.1.1 Chapter Aim

The aim of this chapter is to identify spatial and temporal trends in water quality within the Galloway region and determine to what extent the recovery of water bodies through time has been modified by catchment factors, with a particular focus on the extent to which the presence of forestry is hampering the recovery of freshwaters.

9.1.2 Context - Recovery

UK sulphate emissions have reduced by 70% over the period 1987-2001; during this time deposition has decreased by 60% (Fowler *et al.*, 2004; NEGTAP, 2001). Despite this, Fowler *et al.* (2004) identified no significant trends ($P<0.05$) in deposited acidity (H^+, pH) base cations (Ca, Mg), marine derived ions (Na, Cl), or nitrate. At an international scale Evans *et al.* (2001) reported that across 56 European monitoring sites the emissions reductions have led to the identification of significant downward trends in sulphate at many sites (36 of 56) along with associated reductions of base cations and significant upward trends in ANC. Significant upward trends in pH were found, but are fewer in number (only 19 of 56). Whilst these recovery trends are matched in some areas by fish returns to previously acidified streams (Skjelkvåle et al. 2001; Kroglund *et al.*, 2001; Nyberg *et al.*, 2001), there remains significant concern as to whether acidification still poses a risk to failure of the good ecological status objectives of the Water Framework Directive (Jenkins *et al.*, 2003).

The majority of the sites in the UK Acid Waters Monitoring Network (AWMN) show a statistically significant reduction in sea salt-corrected sulphate levels, with a considerable number of sites showing associated negative trends in base cations, aluminium and chloride and positive trends in pH, alkalinity and ANC (Davies et al., 2005). Charge Balance ANC shows weaker trends than ANC based on alkalinity, and pH shows fewer trends than many of the other variables.

Whilst these data show evidence of recovery at national and international scales and provide hope for the future, studies in the Galloway area have yet to reveal strong indications of recovery despite some evidence of reduced freshwater sulphate. Helliwell *et al.* (2001) used the SEPA long-term dataset to identify long-term trends within the Galloway region. They focussed on three sites: Bladnoch at Glassoch (Site ID 4), Cree at Arnimean (Site ID 15) and Luce at Penwhirn (Site ID 59) (Figure 9-2). Significant trends were identified in both raw and sea salt corrected sulphate (SO_4^* in Table 9-1) as well as chloride and total aluminium, on the afforested Bladnoch and Cree catchments. The moorland Luce catchment only showed significant trends with aluminium (Table 9-1).They note that the statistically significant decline in SO_4 is not enough to lead to an increase in pH within the region and attribute this to the "forest effect" exacerbating sulphate deposition. Similarly, whilst Langan and Hirst (2004) identify negative trends in calcium and sulphate, no trends in pH, nitrate or chloride are identified at the sites of the Loch Dee project (Loch Dee Outflow, Green Burn, Dargall Lane and White Laggan; Site IDs , 34, 36, 37 and 40 respectively) between 1980-2000.

Table 9-1 Trends from Helliwell et al. (2001)

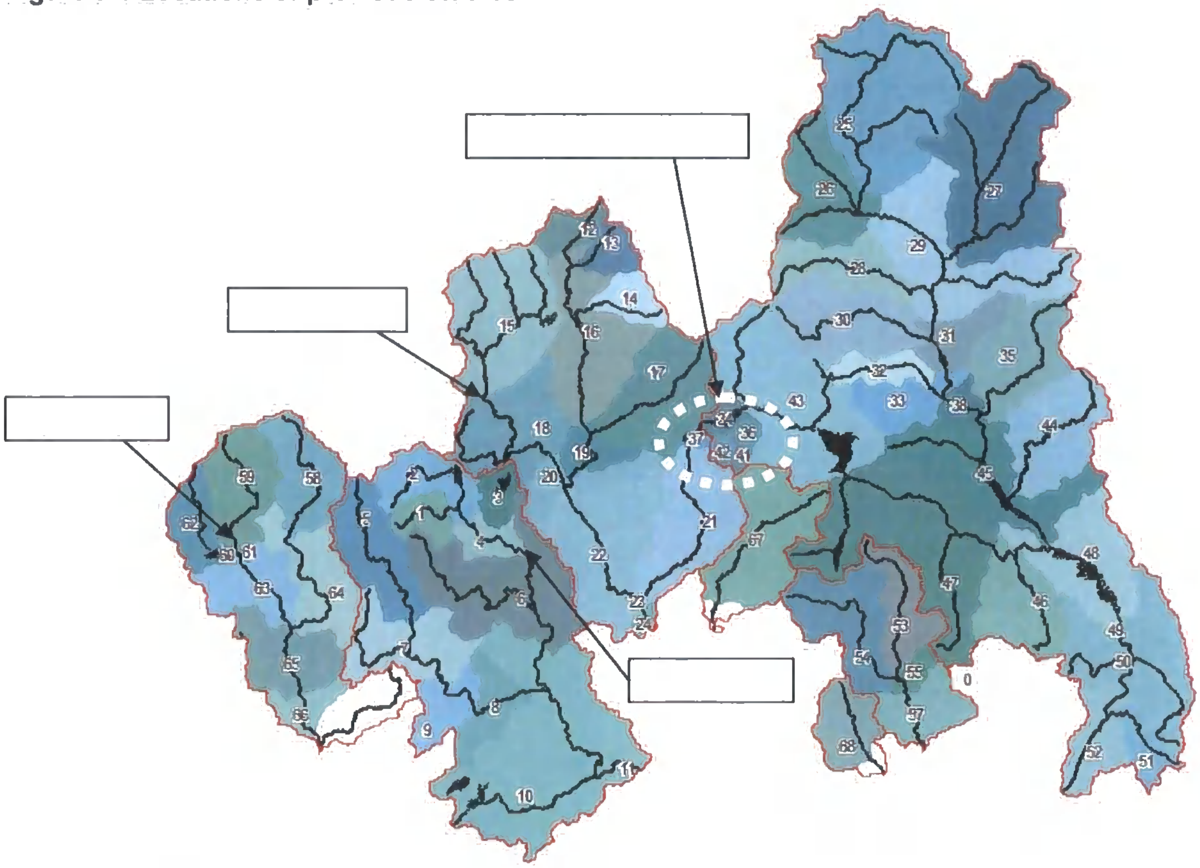
Annual trends in water chemistry based on linear analysis incorporating a seasonal cycle (1984-1999). All trend estimates in $\mu eql^{-1}yr^{-1}$ except pH (pH yr^{-1}). Total Al ($\mu M\ yr^{-1}$). *, ** and *** denotes trends significant at 0.05, 0.01, 0.001 levels, respectively.

	River Cree at Arnimean	*River Bladnoch at Glassoch*	*River Luce at Penwhirn Burn*
pH	-0.00	-0.01	0.01
Na	0.31	-1.30	2.67
K	0.17	[No data]	-0.16
SO_4	-4.11***	-3.08**	-0.98
SO_4^*	-1.34***	-2.32**	-0.02
NO_3	-0.19	-0.32	0.18
Cl	-4.51**	-6.10	-3.12
Total Al	-0.09***	-7.94***	-11.63**
Alkalinity	No data	18.62**	18.86*

9.1.2a Aim 1: Identifying temporal patterns in water quality for Galloway

Despite trends for recovery having been investigated at national (Davies *et al.*, 2005) and international (Evans *et al.* 2001) scales, little work has been realised at regional or catchment scales. This is particularly significant as it is at these scales that landowners can act, and at these scales that water stakeholders will feel the impacts of land management. It is also at these scales that both the Water Framework Directive and current UK forest management policies act. This apparent lack of focus at this scale arises despite the presence of abundant data. The first aim of this chapter is to make use of the SEPA water quality data available in Galloway to identify, for the first time, recovery trends for a variety of acid-prone catchments across the scale of the Galloway region.

Figure 9-1 Locations of previous studies



9.1.2b Aim 2: Spatial patterns in recovery: Identifying the role of forestry.

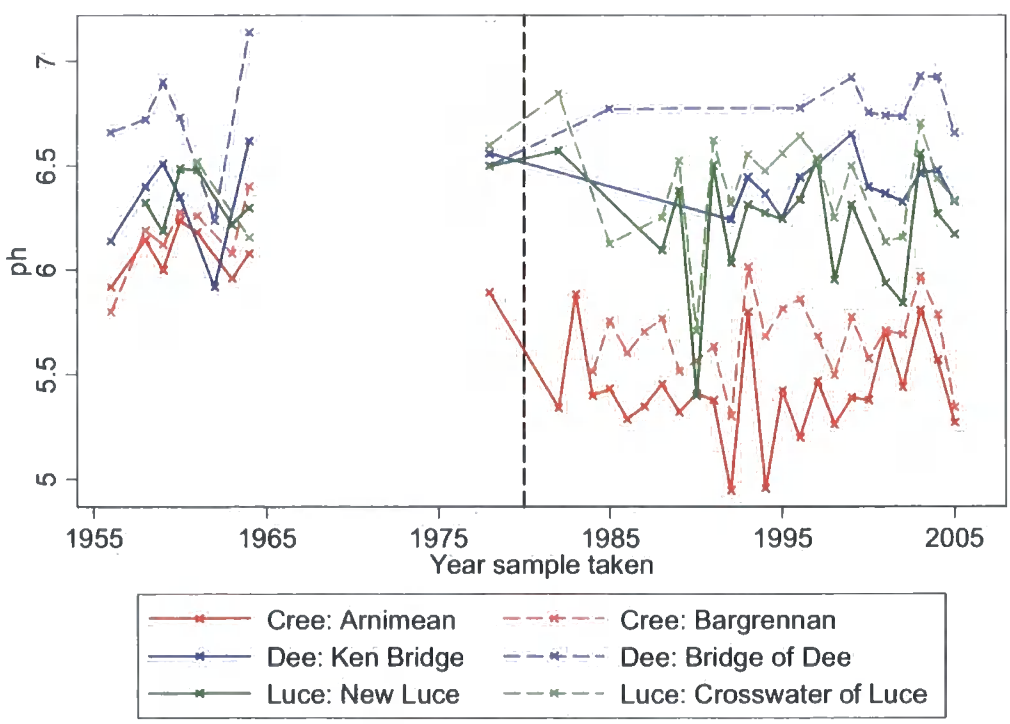
Davies et al. (2005) showed that, for the five acid afforested AWMN sites, three showed no significant trends in acidity indicators, whilst one showed a significant negative trend in alkalinity. Langan and Hirst (2004) also discussed the role of forestry, noting that the 70% afforested Green Burn (Site 36) showed the least sulphate decline of the four Loch Dee sites. Helliwell *et al.* (2001), also cite the forest effect as a reason why a decline in sulphate deposition has not led to a similar decline in pH. Despite this, very little work has been done to examine at a regional scale catchment characteristics that lead to one catchment showing evidence of recovery when its neighbour does not. This determines to what extent the major drivers of acid recovery can be identified, with a particular focus on identifying whether a forest impact can be detected on recovery signals at a regional scale in Galloway.

9.2 Investigating temporal patterns: identifying recovery trends

9.2.1 Study time period

This chapter follows a similar methodology to that used by the Acid Waters Monitoring Network (Davies et al, 2005) for the identification of trends in long-term water quality datasets. Only the long-term dataset from SEPA monitoring is used (processed in section 6.2.2); this focuses on the sites illustrated in Figure 9-1. Figure 9-2 shows the median annual pH for six sites for which long-term data are available; unfortunately due to changes in sampling resolution median chemistry is unavailable for the period 1965-1980. Nevertheless, the shift from pH above six to more acidic conditions is clear for the afforested Cree catchment (red in Figure 9-3) in comparison with the non-forested Luce (green) and the larger, partially afforested Dee catchment (Blue).

Figure 9-2 pH trends 1955-2005 from SEPA long-term data for 6 sites across 3 Galloway catchments. Points are mean annual pH for sites with more than 4 pH records/year.



Driven by the availability of data, and an intention to avoid the 1970s peaks in both sulphate and agricultural lime usage, the period 1980-2005 was selected for this study. This period allows for a fair comparison with the Acid Waters Monitoring Network which commenced in 1988 (Patrick *et al.*, 1991), and means for some of the long-term monitoring sites there are 25 years of data available.

The Acid Waters Monitoring Network use Seasonal Kendall analysis for the significance testing of their trends. This test takes seasonal variations into consideration when determining the significance of a regression line. This method was not applied in this study; instead simple significance testing the statistical comparison of the linear regression coefficient to zero is used. This is not seen as problem, as significant trends can be identified using annual means (Burt *et al.*, 1988; Worrall and Burt, 2007).

In this chapter when the term *significant* is used to describe a trend it indicates that the trend is significant at the level $P<0.05$.

9.2.1a A note on non-forest exacerbated acidity

It should also be noted, regarding Figure 9-2 for the Cree, that the pH in the late 2000s is remains lower than pH 6 below that recorded in the early part of the record. Whilst it is possible that this may result from differences in sampling or analysis it is a strong indication that pH has not yet recovered to the conditions prior to forestry. Appendix H shows the regional distribution of pH from 1955-2006 and also suggests that the return to non-forest-exacerbated acidity may not be a valid argument, as the Luce, Cree and Bladnoch continue to show lower minimum pH values than those found in the 1970s. The influence of changes in monitoring are however difficult to interpret and further analysis of this would be required to more robustly confirm these findings.

9.2.2 Variables for long-term analysis

Table 9-2 Water quality variables for temporal trend analysis

Water Chemistry Data		
✓	pH	For each of these variables the median, mean, maximum and minimum values of a minimum of four annual samples are available. They were extracted from SEPA's monitoring data analysed at SEPA's labs in Dumfries and East Kilbride (see section 6.2.2b)
✓	Cl	
✓	SO_4	
✓	Ca	
✓	Mg	
✓	Na	
✓	K	
✓	xSO_4	Sea salt corrected sulphate values
✓	ANC_{CB}	Charge balance methodology for ANC from major cations and anions
✓	CLoadX	Critical load exceedance using forest and water guideline scenario, ANC=0 and 1995 total S deposition.

✓ included in the analysis *Included, but only between 1984-1998

All water chemistry variables used within the catchment-based database (6.6.1) were investigated with the exception of DOC and ANC_{CA} which were excluded as there was insufficient data and alkalinity was excluded from analysis due to an unreliable record with large amounts of missing data as recommended by Langan and Hirst (2004; see also 6.2.2b). Nitrate data were also excluded, as the values became unreliable after the lab changeover in 1998 (see 6.2.2b) and insufficient data existed before this point. All other variables are analysed in their untransformed states and are shown in μeql^{-1} to allow comparison between variables. The approach of Langan and Hirst (2004) was adopted regarding the sulphate data and any data before 1984 and after 1998 were excluded from any analysis to minimise complications from laboratory changes; this also applied to Critical Loads exceedances and ANC_{CB} both of which are derived in part from sulphate data (see 6.2.2b).

Stream-water chemistry is expected to differ between mean and extreme events (Baker *et al.*, 1996; White *et al.*, 2000; Evans *et al.*, 2007). To account for this, this study focuses on changes in central tendency as described by both the annual median and mean chemistry and uses annual maximum and minimum recorded values at a site as indications of potential extremes. It is important to note that at some sites annual summary statistics are drawn from four samples, usually taken with two in winter and two in summer; whilst these are likely to reflect some of the seasonal variation within the river; it is very unlikely they will be sampling the most extreme conditions. For sites from associated with the Loch Dee project (Sites 34-42 in Table 9-3), the data are collected at much greater temporal frequency (weekly/bi-weekly) and, as a result, these sites are much more likely to sample extreme events; these sites are labelled with an asterisk when referred to below to remind the reader of this fact.

9.2.3 Trend identification methodology

Least squares linear regression is used to identify the relationships among each of the four summary statistics for each water chemistry variable. The regression constant, coefficient and significance were extracted into separate variables for analysis against potential influences on the recovery trend in sections 9.3 and 9.4.

In the analysis that follows tables of regression coefficients are illustrated for all sites where sufficient (> 8 years of >4 data points) data were present. The marker "n/s" is used to identify sites that are not significant at the $P<0.05$ whilst increasing numbers of asterisks are used to mark cells significant at $P<0.05$ (*), 0.01 (**) and 0.001 (***) significance levels.

As the impacts of forestry are the focus of this study the forest cover at each site, as extracted from the SWIR imagery is shown graphically for context using the second Y axis.

9.2.4 *Overview of recovery trends at a regional scale.*

Table 9-3 Long-term trends in water quality variables. A trend is identified if a trend significant at P<0.05 is present in either the mean, median, maximum or minimum.

Catchment	ID	Site	CC2_2005 (%)	so4	xso4	pH	Cl	Na	Ca	Mg	K	CloadX	ANC_CB
Bladnoch	2	Waterside	44			#	#	#	#	#	P		
Bladnoch	4	Glassoch Bridge	45			#	#	#			#		
Bladnoch	6	A75 Shennaton	39	(#)	(#)	#	#	(#)			(#)		
Bladnoch	10	Torhouse Mill	23	N	#	#	#	#			P		
Cree	15	Arnimean	36	N	N	#	N	#			P		
Cree	16	Stroan Bridge	22	N	N	#	N	N			P		
Cree	17	Trool Footbridge	16	N	N	P	N	N			N		
Cree	18	Bargrennan	34	N	N	#	#	#			#		
Cree	19	Minnoch Bridge	21			#	#						
Cree	21	Penkiln Burn	18	N	N	P	N	#			P		
Cree	23	Newton Stewart GS	26	N	N	#	#	#					
Dee	26	Liggat Bridge	37	(#)	(#)	N	#	#			#		
Dee	27	High Bridge of Ken	22			#	#						
Dee	34	Loch Dee Outflow*	15	N	N	P	#	#	N	N	N	N	P
Dee	36	Green Burn*	43	N	N	#	#	#	N	#	N	N	P
Dee	37	Dargall Lane*	0	N	N	P	#	#	#	#	#	N	P
Dee	38	Ken Bridge	26			P	#						
Dee	40	White Laggan 2*	10	N	N	P	#	#	N	#	#	N	P
Dee	41	Black Laggan Burn*	13	N	N	P	#	#	#	#	N	N	P
Dee	42	White Laggan 3*	5	N	N	P	#	#	N	#	N	N	P
Dee	46	Mossdale	33			(#)	(#)						
Dee	47	Stroan Viaduct	29			P	#	#			P		
Dee	49	Glenlochar GS	23	N	N	N	#	#			#		
Dee	50	Bridge of Dee	22			#	#						
Fleet	53	Little Water of Fleet	46			#							
Fleet	54	Big Water of Fleet	32			P							
Fleet	57	Gatehouse Tidal	28			(#)	(#)						
Luce	58	Dirniemow	15			(P)	(#)	(N)	(P)	(P)	(#)		
Luce	59	Luce u/s Penwhirn	6	(#)		#	#	#			N		
Luce	60	Dalhabboch Bridge	30			#	(#)						
Luce	63	New Luce	10			#	P						
Luce	64	Crosswater at New Luce	8	(#)	(#)	#	#						
Luce	65	Airyhemming GS	8	N	N	#	#	#			P		
Luce	66	Glenluce Viaduct	8			(#)	(#)						
Palnure Burn	67	Palnure Burn	33	N	N	#	#	#			N		
Skyre Burn	68	Skyre Burn	0			(#)	(#)						

Trends significant at P<0.05: P=Positive, N=Negative, #=Trend not significant at P<0.05.
Cells are blank if there is insufficient data to perform a regression.
Trends in brackets are based on less than 10 data points.

Table 9-4 summarises the trends statistically significant at $P<0.05$ identified in the Galloway Water quality data series. A site is identified as having a trend if a significant trend is identified with any of the summary statistics, median, minimum, maximum or mean. There were no instances where summary statistics at a site showed different directions of trend for significant trends. Trend directions are determined by whether the coefficient of the linear regression is above or below zero.

9.2.4a pH and Sulphate overview

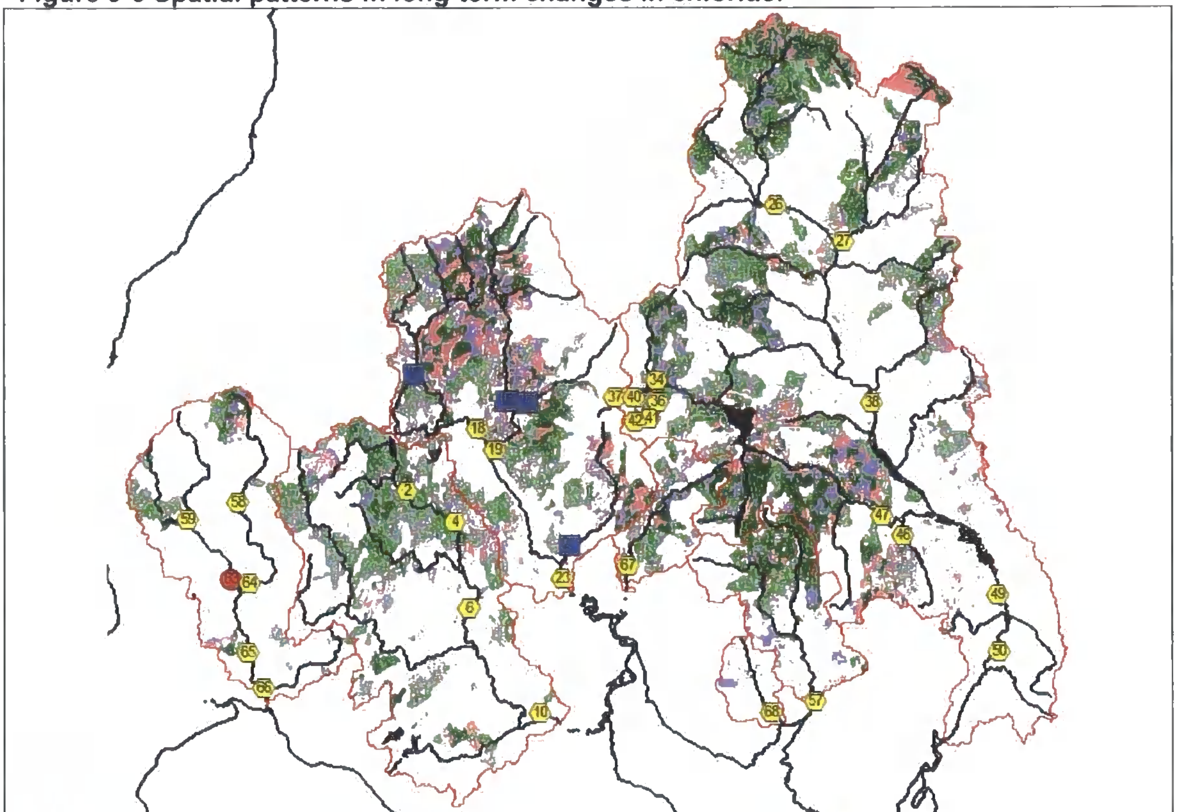
Taking the region as a whole, it is clear that significant negative trends in sulphate deposition are identified at around 80% of the Galloway sites, during the time period of trustworthy SEPA sulphate data (1984-1998). Significant trends in pH are much more rare however, with 22 of the 35 sites (63%) showing no significant trend. Of the sites showing significant trends these are mainly positive in nature (at 11 sites) with only two sites in the Dee showing negative trends. It is interesting to note that the only site from the Loch Dee project not showing a significant upward trend in pH is the 70% afforested Green Burn; this was also noted by Langan and Hirst (2004). Trends in sulphate and pH are not discussed in more detail here as sections 9.3 and 9.4 are devoted to them.

9.2.4b Marine ions

Similar to the pattern seen in the AWMN sites (Davies *et al.*, 2005; Monteith and Shilland, 2007), there are very few significant trends in marine ions: only 5 of the 33 sites show significant trends in chloride, and two of these show no significant trend with sodium. Of these significant trends, one is positive and four negative. The negative trends are identified at three sites within the Cree catchment. It is worth noting that all four sites showing significant decreases in freshwater chloride all have experienced a reduction in forestry cover since 1989 (pink/blue upstream in Figure 9-3). This decrease in chloride would fit with hypothesis that a decrease in chloride scavenging resulted from felling. Similarly the statistically significant increase in chloride at the Luce site 63 matches with an increase in forestry upstream of that site (Figure 9-4).

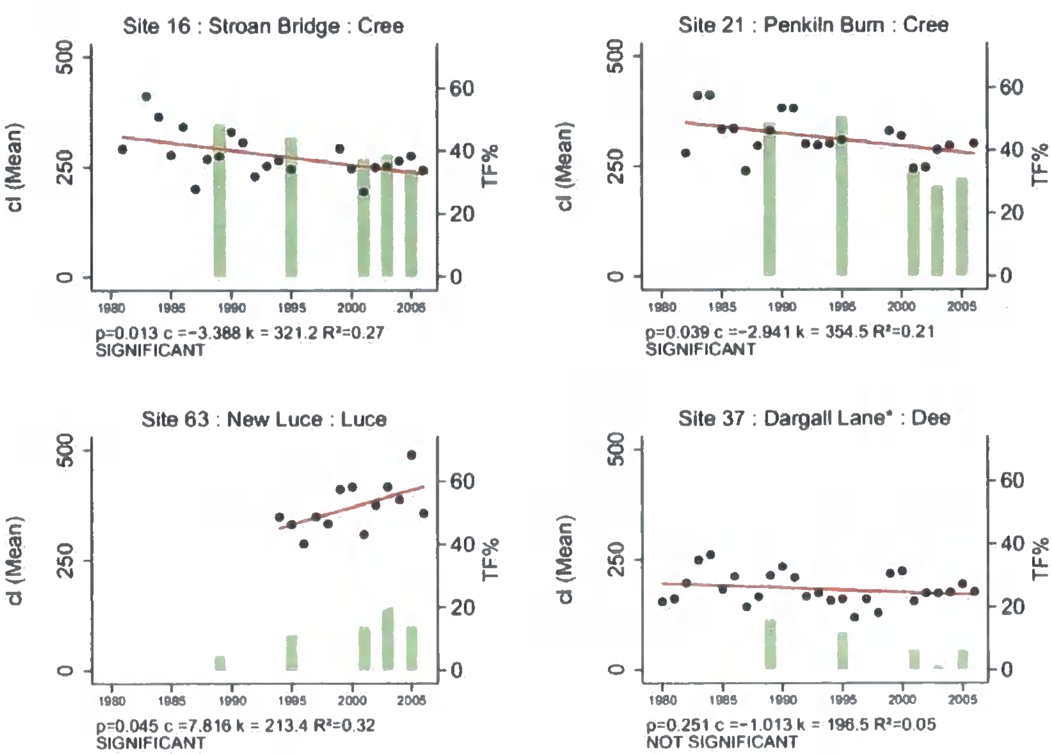
Figure 9-5 shows that the four negative trends are indeed identified amongst those areas with the greatest change in forestry between 1995 and 2005 (between 8.8% and 19.6% of the catchment), and that the positive trend corresponds to a site with a relatively small increase in forestry ($\approx$2.5% catchment) in an area of high chloride deposition (>360μeq/l).

Figure 9-3 Spatial patterns in long-term changes in chloride.



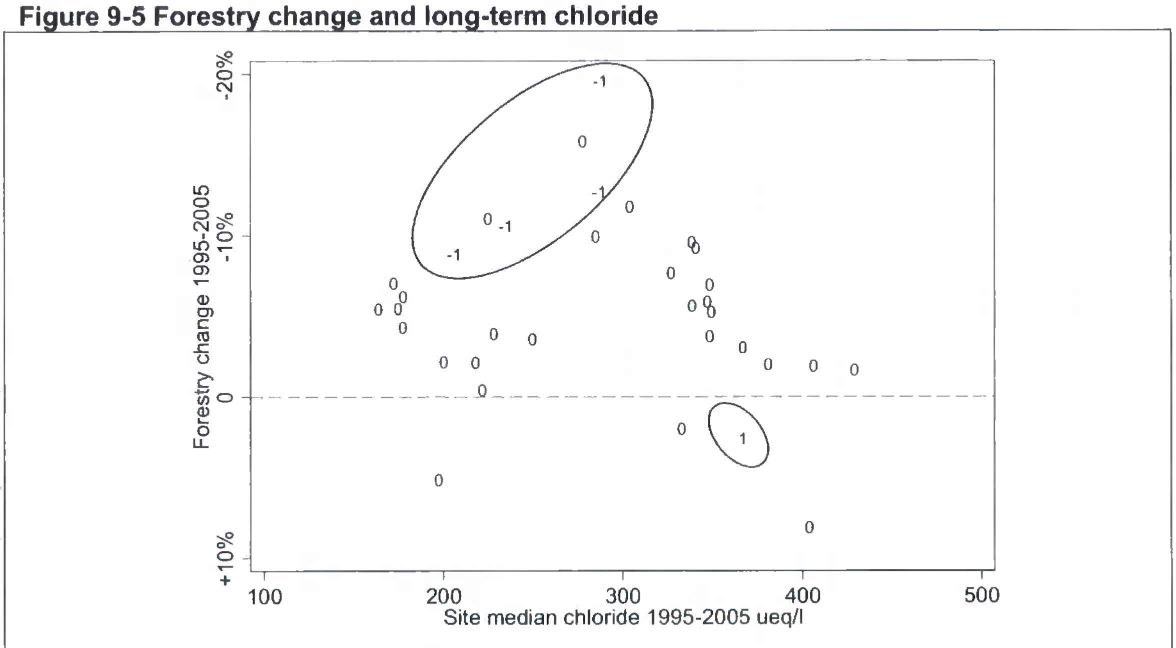
	Positive Trend		No significant trend		Negative Trend
	Non-forest		Forestry felled 1995		Forestry felled 2005
	Forestry establishing 1989-2005				Established forest
N	Number in circle refers to site ID see Table 9-1				

Figure 9-4 Long-term trends in chloride (Cl units: μeql^{-1})



Only forestry is considered as an impact here and it is clear that there are other factors, particularly patterns in climate such as climate change (Wright *et al.*, 2006) and the NAO (Monteith *et al.*, 2000; Hindar *et al.* 2004), that will also contribute to chloride in freshwaters. Nonetheless, the trends indicated fit well with the recognised forest scavenging effect and indicate that change in forest cover can lead to changes in the ion-balance which may complicate freshwater recovery. The value of long-term forestry data are also made apparent, as without detailed forest maps forest change would be difficult to quantify.

Figure 9-5 Forestry change and long-term chloride



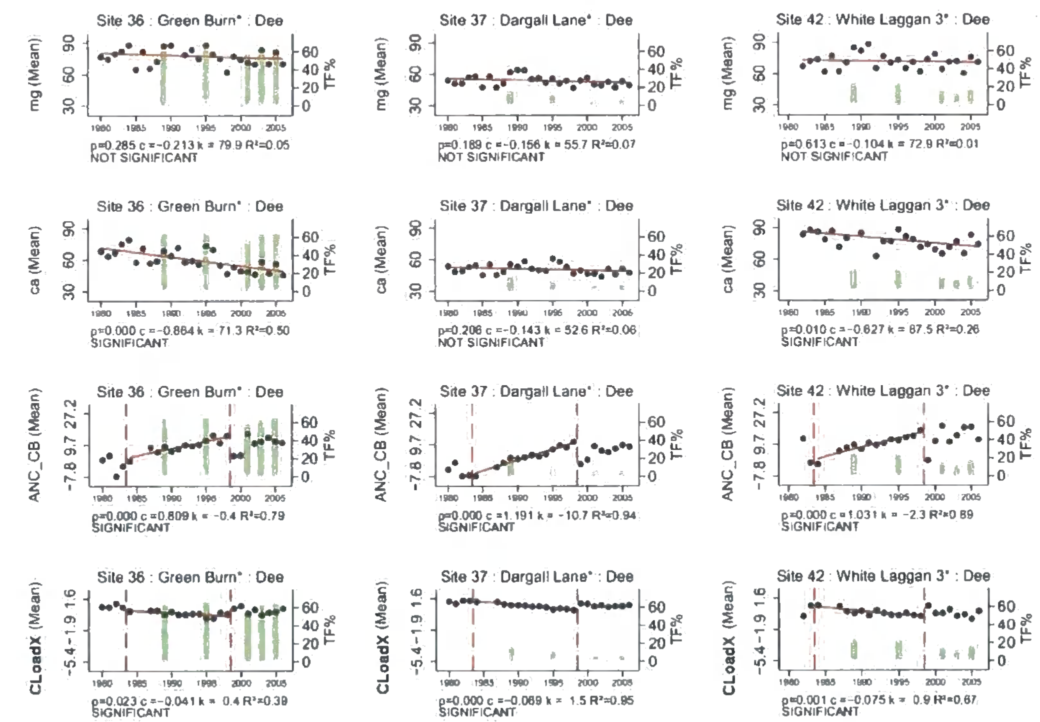
1	Positive trend	0	No significant trend	-1	Negative trend

Referring back to Figure 9-4 it is also important to note that although significant trends are identified in some sites in spite of seasonal variations (Figure 9-4a-c), the Dargall Lane data show no significant trend using simple linear regression even when the same period is analysed. This site was identified by the AWMN as showing a significant (at $P<0.05$) decrease in chloride of -3.94 $\mu eq\ year^{-1}$ over the period 1988-2003 using seasonal Kendall approaches (Davies *et al.*, 2005). This was checked using the existing data which showed no evidence of a significant trend over the same period (1988-2003), and in fact showed some evidence of a decrease in significance due to increases in chloride in recent years. The lack of significant trend based on raw data in comparison with significant trends from seasonally-corrected data indicates that seasonal extreme events, themselves influenced by NAO fluctuation (Monteith *et al.*, 2000), are playing a role in limiting the detection of recovery.

9.2.4c Changes in base cations

Little base cation data are available for sites outside of the Loch Dee project, particularly in the cases of calcium and magnesium. Significant negative trends in calcium levels which would suggest recovery are identified in all sites but the Dargall Lane whilst magnesium only shows a significant trend at the Loch Dee outflow. Potassium data are available for a larger numbers of sites, 18, of which six show positive trends, seven negative and eight no significant trend.

Figure 9-6 Long-term trends in base cations, ANC and critical loads exceedance at Loch Dee sites (Ca, Mg and ANC_{CB} units: μeql^{-1}; CLoadX units: keq $ha^{-1}y^{-1}$)



Critical Loads exceedance and Charge Balance ANC data are available only for the sites at the Loch Dee project. Both variables show highly significant evidence of recovery with a reduction in critical load exceedance and an increase in ANC shown at all sites.

In conclusion, it is clear that emissions reductions appear to have reduced the amount of sulphate reaching the freshwater environment, and that in some areas of Galloway this is leading to a recovery in terms of increasing pH. Results from the Loch Dee project reinforce this pattern by showing that the increase in pH is also being matched by an increase in charge balance ANC, and a decrease in base cations and Critical Loads exceedance. This situation is far from the case at all sites and 23 of the 35 of the sites still show no evidence of an upward trend in pH. The following sections look in more detail at the catchment factors that contribute to trends in freshwater sulphate and water quality as represented by pH.

9.3 Freshwater sulphate response to reduced deposition

9.3.1 Temporal trends in xSO4

Table 9-5 Trends in excess sulphate (all units $\Delta\mu eql^{-1}$)

Catchment	ID	Site	N	c (Median)	c (Mean)	c (Min)	c (Max)
Cree	18	Bargrennan	15	-3.13***	-3.38***	-2.12***	-7.44***
Luce	65	Airyhemming GS	15	-3.01***	n/s	n/s	n/s
Dee	49	Glenlochar GS	15	-2.98***	-3.31***	-1.74***	-5.75***
Cree	21	Penkiln Burn	12	-2.78***	-2.54**	-3.41**	-3.15***
Cree	15	Arnimean	15	-2.68***	-3.354***	-1.192**	-6.603**
Palnure Burn	67	Palnure Burn	12	-2.46***	-2.57**	n/s	-2.81***
Cree	23	Newton Stewart GS	14	-2.19***	n/s	n/s	n/s
Dee	40	White Laggan 2*	15	-2.07***	-2.00**	n/s	n/s
Dee	36	Green Burn*	15	-1.90***	-1.51**	n/s	n/s
Cree	16	Stroan Bridge	12	-1.88***	n/s	n/s	n/s
Dee	34	Loch Dee Outflow*	15	-1.86***	-1.73**	-0.93**	n/s
Dee	41	Black Laggan Burn*	15	-1.84***	-1.95**	-1.03**	n/s
Dee	42	White Laggan 3*	15	-1.84***	-1.94***	-1.27**	n/s
Dee	37	Dargall Lane*	15	-1.72***	-1.58**	n/s	-2.00***
Cree	17	Trool Footbridge	12	-1.50***	-1.42**	n/s	-2.36***
Luce	64	Crosswater at New Luce	6	(n/s)	(n/s)	(n/s)	(n/s)
Bladnoch	10	Torhouse Mill	14	n/s	n/s	n/s	n/s
Dee	26	Liggat Bridge	6	(n/s)	(n/s)	(n/s)	(n/s)
Bladnoch	6	A75 Shennaton	6	(n/s)	(n/s)	(n/s)	(n/s)

Significant trends marked as follows: * $P<0.05$ ** $P<0.01$ *** $P<0.001$

Coefficients in xSO_4 $\mu eql^{-1}year^{-1}$

Sites sorted by median xSO_4

Table 9-6 Significance (P<0.05) by summary statistic

	c(Median)	c (Mean)	c (Min)	c (Max)
Significant	15	12	7	7
Not Significant	4	7	12	12
Total	19			

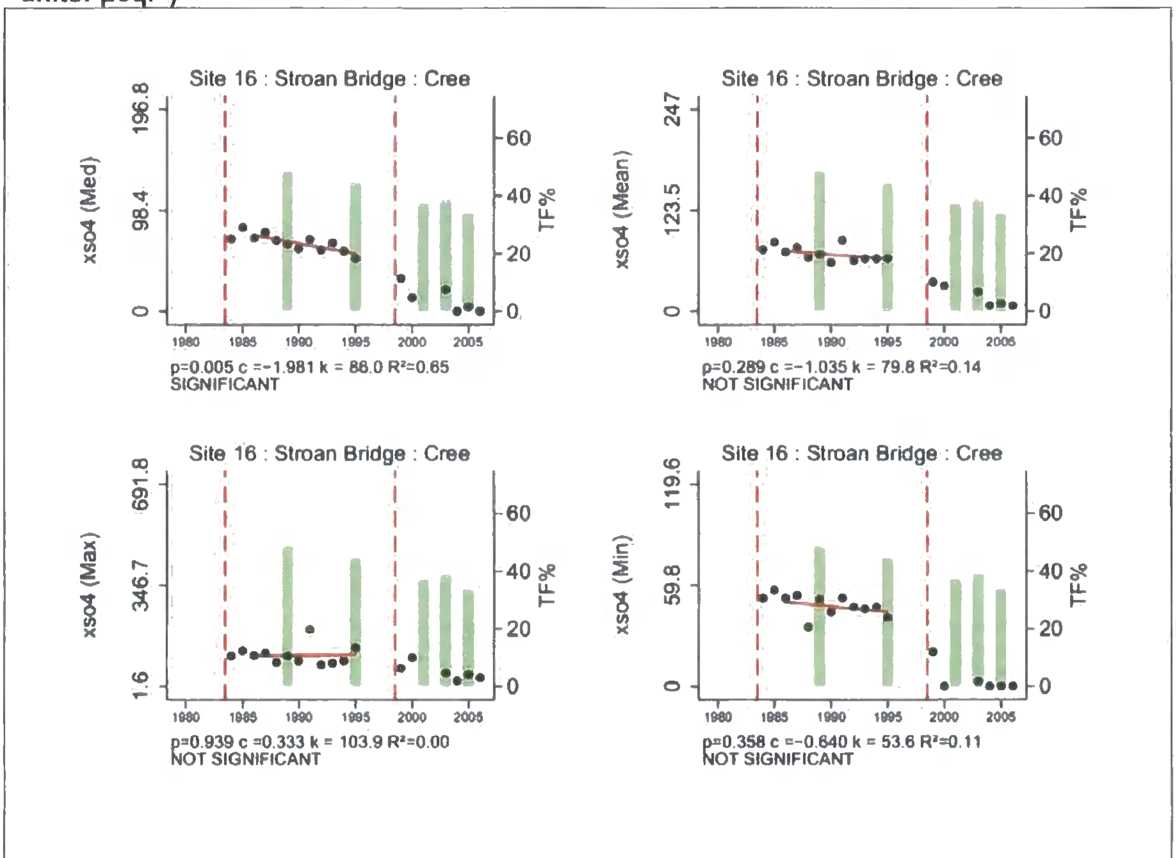
Trends in anthropogenic sulphate (xSO_4), where present, decline between -1.42 > c > -3.38 $\mu eql^{-1}year^{-1}$ for median chemistry, and a decline of maximum xSO_4 of -2.00 > c > -7.44 $\mu eql^{-1}year^{-1}$ (Table X)[22]. It is notable that there are more significant trends of xSO_4 identified with indicators of central tendency than with the extremes (Table 9-6); furthermore, the median identifies more significant trends than the mean. This indicates that i) even with a relatively low number of sampling points per year, the median

[22] C is used here to represent the coefficient of the regression line see Table 8-6

successfully represents changes in water chemistry and ii) outlying extreme events appear to prevent trends in recovery being identified at maximum and minimum water chemistry. This second fact is particularly significant, as it is change in trends in extreme water chemistry is most likely to be ecologically beneficial, as even an individual acid flush can have a significant impacts on fish stocks (Evans *et al.*, 2007).

Figure 9-7 illustrates the influence of a single extreme event on the detection of trends at Stroan Bridge in the Cree system; here an outlying maxima in 1991 and minima in 1989 prevent a significant trend being identified from the mean.

Figure 9-7 Influence of outliers on trends in xSO_4 detected by regression analysis (xSO_4 units: μeql^{-1})

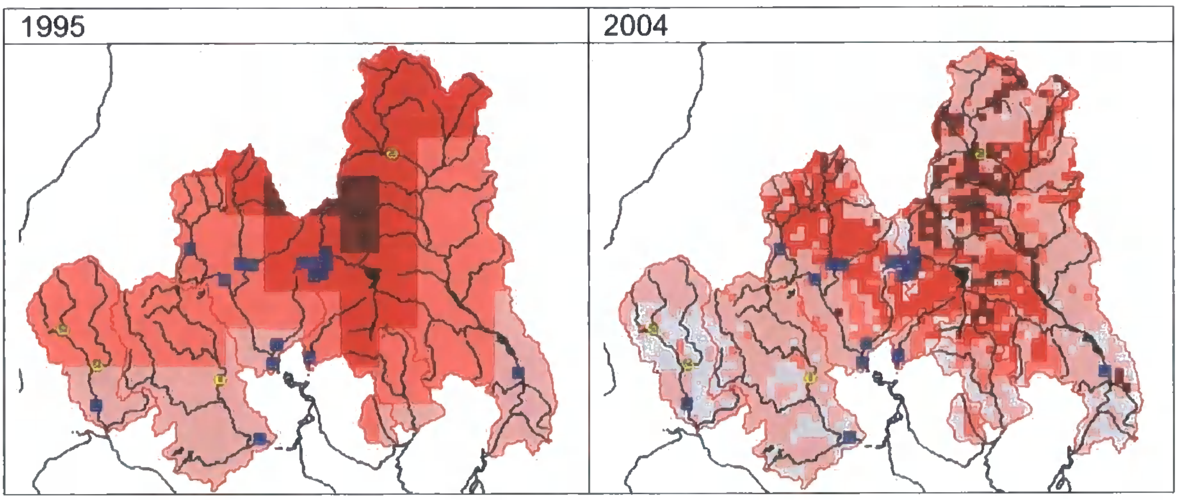


Trends in raw sulphate are very similar to those in anthropogenic sulphate (for comparisons see Table 9-2) and as such are not discussed in depth here. There is however one site at Torhouse Mill in the Bladnoch system where a significant trend is identified in total sulphate but not in sea salt corrected sulphate. This serves as a reminder that the sea salt correction itself is capable of masking trends in recovery in more ecologically relevant variables.

9.3.2 Spatial patterns in freshwater xSO4 recovery

Changes in freshwater sulphate are expected as a response to the decline in the deposition of anthropogenic sulphate. Figure 9-8 shows the spatial pattern of freshwater xSO_4 recovery overlain on the two CEH total S deposition products for 1995 and 2005. The spatial pattern of recovery is shown to reflect the spatial pattern in sulphur deposition; this is to be expected as areas with high total S loadings in the 1990s are likely to see more recovery than those areas where the total S load is unchanged.

Figure 9-8 Spatial distribution of sulphate recovery trends overlaid on the two Total S deposition datasets (CEH, Hall *et al.*, 2004).



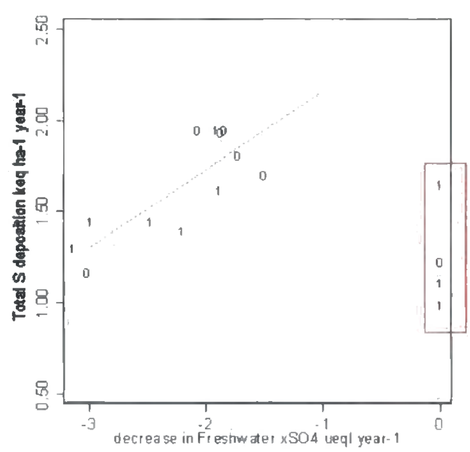
	Positive Trend				0 – 0.5 keq ha-1 yr-1
	No significant trend		0.5 – 1 keq ha-1 yr-1		1- 1.5 keq ha-1 yr-1
	Negative Trend		1.5 – 2 keq ha-1 yr-1		> 2 keq ha-1 yr-1
N	Number in circle refers to site ID see Table 9-1				

Figure 9-8 shows the patterns of sulphur deposition from the two CEH total S deposition products. It is important to note that the two products are very different in nature with the 1995 model mapped at $5km^2$ and including no land use information. The 2004 product available for this project separates deposition by land use based on land cover information; as a result it is not possible to display total S deposition divorced from forest impact, and in many areas sulphur appears to have increased solely as a result of increased modelling precision. The 2004 product is likely to provide a more realistic impression of sulphur deposition, but the two layers must be compared with care. The 1995 layer is used to represent total S in the analyses below to ensure that the forestry variables generated by this project are used to represent forestry without the collinearity with the 2004 total S data. A change map between the two layers is also meaningless as it is impossible to differentiate changes of deposition from changes in methodology. The two are interpreted in tandem, with an understanding of the differences they present.

Sulphate recovery is shown to be widespread, particularly in the Dee and Cree systems where total S loads are over 1keq ha^{-1} $year^{-1}$. A sulphate recovery variable was generated as the coefficient of the Median recovery regression line where the regression was significant at P<0.05. This was then used in regression analysis using catchment sulphate deposition in 1995 as the independent variable. The resulting regression line is presented in Figure 9-9. The four sites without significant trends are also shown in the figure (at x=0); these sites were excluded from the regression analysis.

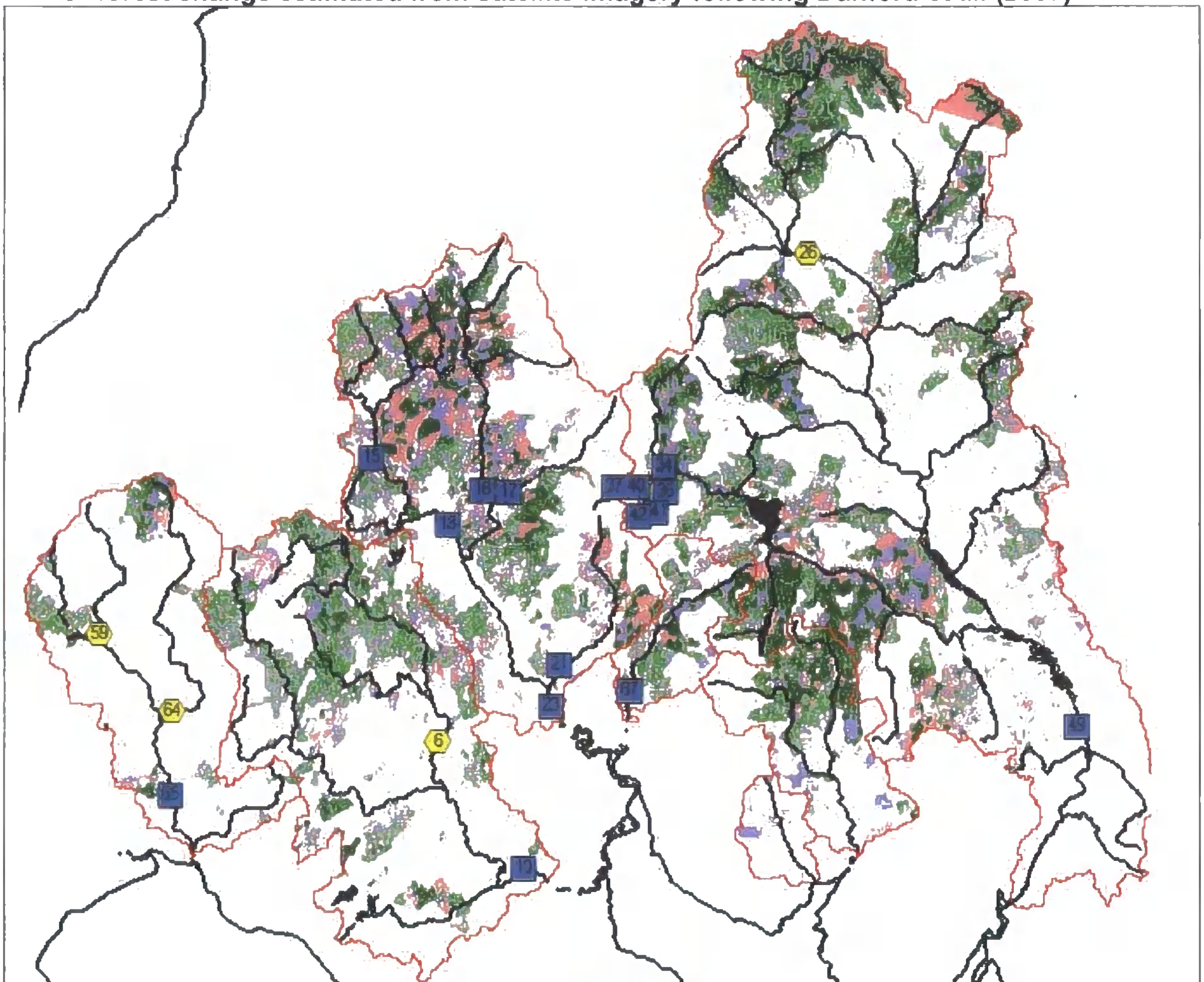
The analysis shows that for the 14 sites where recovery is apparent, a statistically significant positive trend ($P < 0.001$, $R^2 = 0.66$, RMSE = 0.174 keq ha^{-1} $year^{-1}$) exists between freshwater xSO_4 decline and level of sulphate deposition (Figure 9-9). Areas with higher sulphate deposition in 1995 have shown slower recovery with trends in freshwater xSO_4 recovery closer to zero.

Figure 9-9 Relationship between total S deposition, recovery and forestry. Red box sites show no statistically significant trend in xSO_4. Sites marked 1 have over 30% total forestry; sites marked 0 have less than 30% total forestry.



In terms of the role of forestry, it is interesting to note that of the four sites not showing a recovery in freshwater xSO_4, three are afforested sites (Figure 9-9). The fourth site, in the Luce catchment, is only lightly afforested (11%). Whilst a sample of four is not sufficient to draw any statistical conclusions, the prevalence of forest sites amongst those without signs of recovery adds weight to the body of evidence for a forest effect on recovery (Helliwell *et al.*, 2001; Langan and Hirst, 2004; Davies *et al.* 2005).

Figure 9-10 Regional patterns in sulphate recovery from long-term SEPA data compared with forest change estimated from satellite imagery following Dunford *et al.* (2007)



	No Forestry		Forestry Felled by 1995
(yellow hexagon)	No xSO_4 recovery		Forestry Felled by 2005
(blue square)	xSO_4 recovery identified		Forestry establishing 1989-2005
Number at point is catchment forestry percentage in 2005.			Established forest 1989-2005

9.4 Trends in freshwater recovery using pH

In the sections that follow freshwater pH is used as the key response variable for the discussion of freshwater recovery from sulphate deposition. This is for three reasons. Firstly, whilst freshwater xSO_4 can be assumed to originate from the deposition of anthropogenic sulphur compounds, freshwater pH is a product of both atmospheric inputs and catchment factors including land use, vegetation, bedrock geology and soils. Secondly, pH has been shown to be ecologically relevant with pH 5.5 seen as a critical level (Harriman, 1988) and pH 4.5. Finally, pH is the variable for which the largest number of sites had long-term records available, and for which trends were discerned, making it the largest recovery dataset available for this analysis.

Table 9-7 Long-term trends in pH shown by regression analysis using SEPA long-term monitoring data showing both trends in central tendency and extremes.

Catchment	ID	Site	xSO_4 Median Trend	N (Years)	k (1980 Median)	c (Median)	c (Mean)	c (Min)	c (Max)
Dee	37	Dargall Lane*	-1.72***	27	5.2	0.03***	0.02*	0.01***	n/s
Dee	47	Stroan Viaduct		16	4.5	0.03*	0.03*	n/s	0.06**
Cree	17	Trool Footbridge	-1.50***	21	5.1	0.02**	0.01*	n/s	n/s
Dee	41	Black Laggan Burn*	-1.84**	25	5.9	0.02*	0.01*	n/s	0.01**
Cree	15	Arnimean	-2.68**	25	5.4	0.01*	n/s	n/s	n/s
Cree	21	Penkiln Burn	-2.78**	22	6.6	0.01*	0.01*	n/s	n/s
Dee	34	Loch Dee Outflow*	-1.86**	27	5.5	0.01**	0.01**	n/s	n/s
Dee	40	White Laggan 2*	-2.07***	26	6.2	0.01*	0.01**	0.01*	n/s
Dee	42	White Laggan 3*	-1.84**	25	6.0	n/s	0.01*	n/s	n/s
Fleet	54	Big Water of Fleet		15	6.1	n/s	n/s	0.07*	n/s
Luce	58	Dirniemow		8	6.1	(n/s)	(n/s)	(0.06*)	(n/s)
Dee	38	Ken Bridge		14	6.2	n/s	n/s	0.05*	n/s
Dee	49	Glenlochar GS	-2.98***	27	6.8	n/s	-0.01***	n/s	-0.01**
Dee	26	Liggat Bridge	(n/s)	20	6.1	n/s	n/s	-0.01*	n/s
Bladnoch	10	Torhouse Mill	n/s	21	7.0	n/s	n/s	n/s	n/s
Cree	18	Bargrennan	-3.13***	23	5.7	n/s	n/s	n/s	n/s
Luce	65	Airyhemming GS	-3.01*	27	6.7	n/s	n/s	n/s	n/s
Palnure Burn	67	Palnure Burn	-2.46*	20	6.3	n/s	n/s	n/s	n/s
Cree	23	Newton Stewart GS	-2.19*	22	6.5	n/s	n/s	n/s	n/s
Dee	36	Green Burn*	-1.90**	27	5.8	n/s	n/s	n/s	n/s
Cree	16	Stroan Bridge	-1.88**	22	5.8	n/s	n/s	n/s	n/s
Bladnoch	6	A75 Shennaton	(n/s)	20	6.1	n/s	n/s	n/s	n/s
Luce	64	Crosswater at New Luce	(n/s)	20	6.2	n/s	n/s	n/s	n/s
Bladnoch	2	Waterside		11	4.6	n/s	n/s	n/s	n/s
Bladnoch	4	Glassoch Bridge		14	5.2	n/s	n/s	n/s	n/s
Cree	19	Minnoch Bridge		12	6.0	n/s	n/s	n/s	n/s
Dee	27	High Bridge of Ken		18	6.9	n/s	n/s	n/s	n/s
Dee	46	Mossdale		8	7.1	(n/s)	(n/s)	(n/s)	(n/s)
Dee	50	Bridge of Dee		10	6.9	n/s	n/s	n/s	n/s
Fleet	53	Little Water of Fleet		15	5.6	n/s	n/s	n/s	n/s
Fleet	57	Gatehouse Tidal		8	7.3	(n/s)	(n/s)	(n/s)	(n/s)
Luce	59	Luce u/s Penwhirn		13	6.5	n/s	n/s	n/s	n/s
Luce	60	Dalhabboch Bridge		15	5.6	n/s	n/s	n/s	n/s
Luce	63	New Luce		19	6.1	n/s	n/s	n/s	n/s
Luce	66	Glenluce Viaduct		8	6.0	(n/s)	(n/s)	(n/s)	(n/s)
Skyre Burn	68	Skyre Burn		8	8.0	(n/s)	(n/s)	(n/s)	(n/s)

Significant trends marked as follows: *** P<0.05** **** P<0.01** ***** P<0.001**

xSO_4 Coefficients in $\Delta\mu eql^{-1}$; pH trends in ΔpH units

9.4.1 Temporal Trends in pH

Far fewer significant trends are identified in terms of pH than were identified in terms of anthropogenic sulphate. The majority of significant trends in pH are positive, in the order of $0.01 < c < 0.03$ pH units year^{-1} with median pH. Unlike anthropogenic sulphate, there is no one summary statistic that identifies all significant trends; instead, trends are identified with both indicators of central tendency and extremes, and sites are identified with significant trends in one and not the other.

Figure 9-11 Comparing trends in central tendency and extremes for three long-term SEPA monitoring sites within the Galloway area showing positive trends in pH.

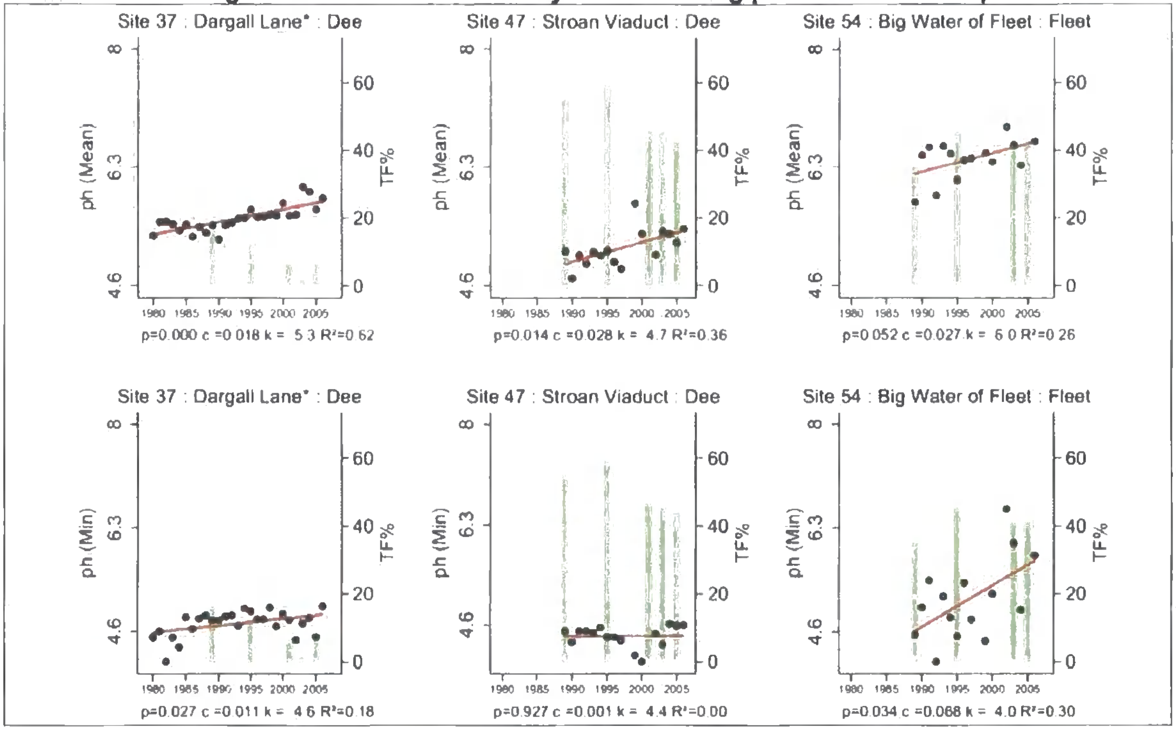


Figure 9-9 highlights this with examples from the three sites showing the greatest significant trends. The Dargall Lane in the Dee system shows an increase of 0.011 and 0.018 pH units year^{-1} respectively with both minimum and mean pH whilst the Stroan Viaduct site shows no significant increase in minimum pH, but a significant increase of 0.028 pH units year^{-1} and the Big Water of Fleet shows the opposite with an increase in minimum pH of 0.068 pH units a year^{-1} not matched by a significant increase in mean pH.

The differences between the summary statistics is important to note both in terms of the significance of extreme pH events to ecology, and the selection of indicators for monitoring freshwater recovery; trends in the median may not be enough to protect sensitive species, and a non-significant median trend may mask more subtle recovery trends at the extremes. Similar effects are also shown in sites with negative trends in pH (Cf. Figure 9-13).

It is also important to note that not every site where a decrease in anthropogenic sulphate is identified is matched by a resultant significant increase in pH (Figure 9-12). In cases such as sites 23 and 65 in Figure 9-12 additional years of data may improve the significance of the trend, with the existing coefficients, though highly insignificant (P>0.3) at least indicate positive trends. Sites such as the Green Burn, loch Dee's afforested catchment show no indication of improvement, with no significant trend identifiable and a large amount of scatter despite a significant decrease in sulphate in the order of -1.9 μeql^{-1} $year^{-1}$.

Figure 9-12 Comparing trends in xSO4 and pH for three long-term SEPA monitoring sites within the Galloway area showing negative trends in sulphate but not in pH.

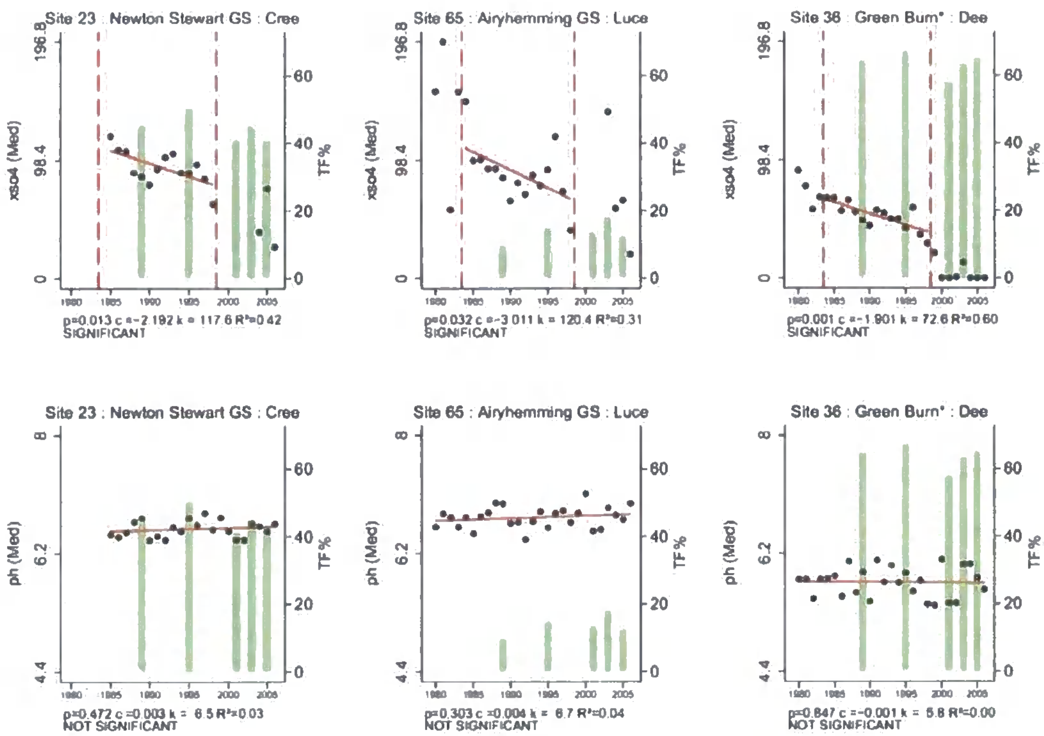
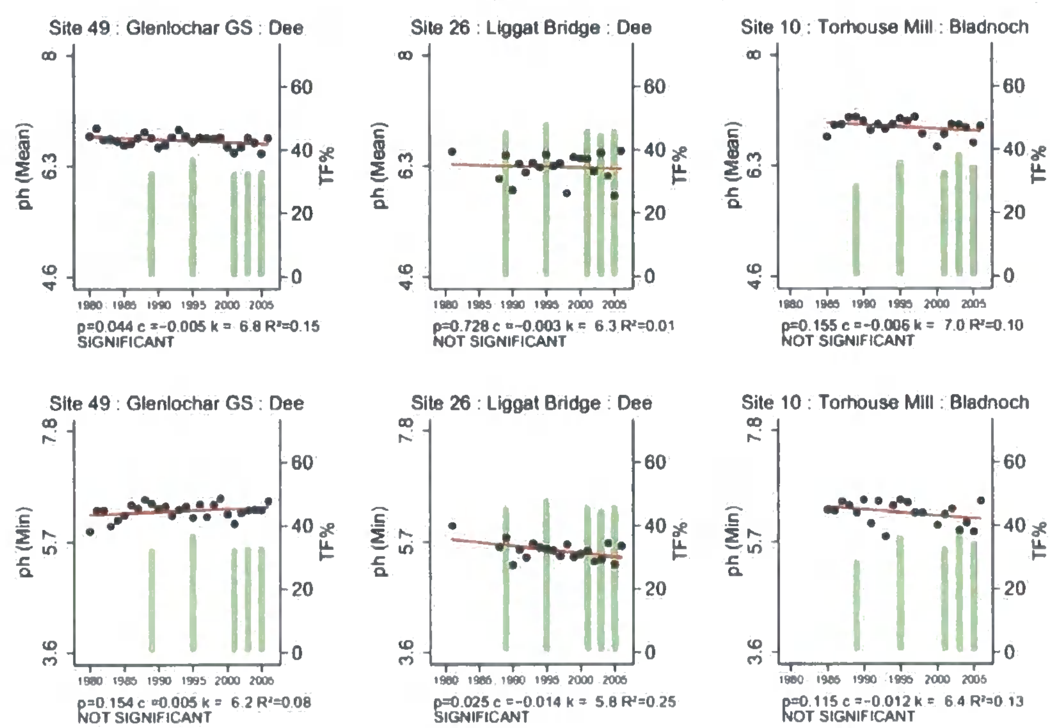


Figure 9-13 Comparing trends in central tendency and extremes for three long-term SEPA monitoring sites within the Galloway area showing negative trends in pH.



Furthermore, whilst the majority of statistically significant trends identified were positive in direction, negative trends in pH were still apparent at some sites within the region (Figure 9-13). This is particularly significant as it indicates that despite the emissions reductions, and evidence of improvements elsewhere, conditions in specific catchments are still experiencing worsening environmental conditions. In terms of the management of the water environment, these findings stress that it is not yet possible to conclude that recovery will take place in all catchments as a result of decreases in pollutant load. To meet the needs of the WFD it will be necessary to match management practices to the requirements of individual catchments to meet the targets of good ecological status set by the WFD. As above, it is notable that trends present in site central tendency values are not necessarily matched by trends in the extremes and vice versa (Cf. Figure 9-11).

It is also important to note that the two sites with significant negative trends in pH despite the 70% decrease in sulphate deposition are both forested with over 30% of the catchment under forestry since 1989. Whilst impossible to draw further conclusions with a sample of two, this fact reinforces the work of others suggesting a "forest effect" on recovery.

9.4.2 Spatial analysis of pH recovery

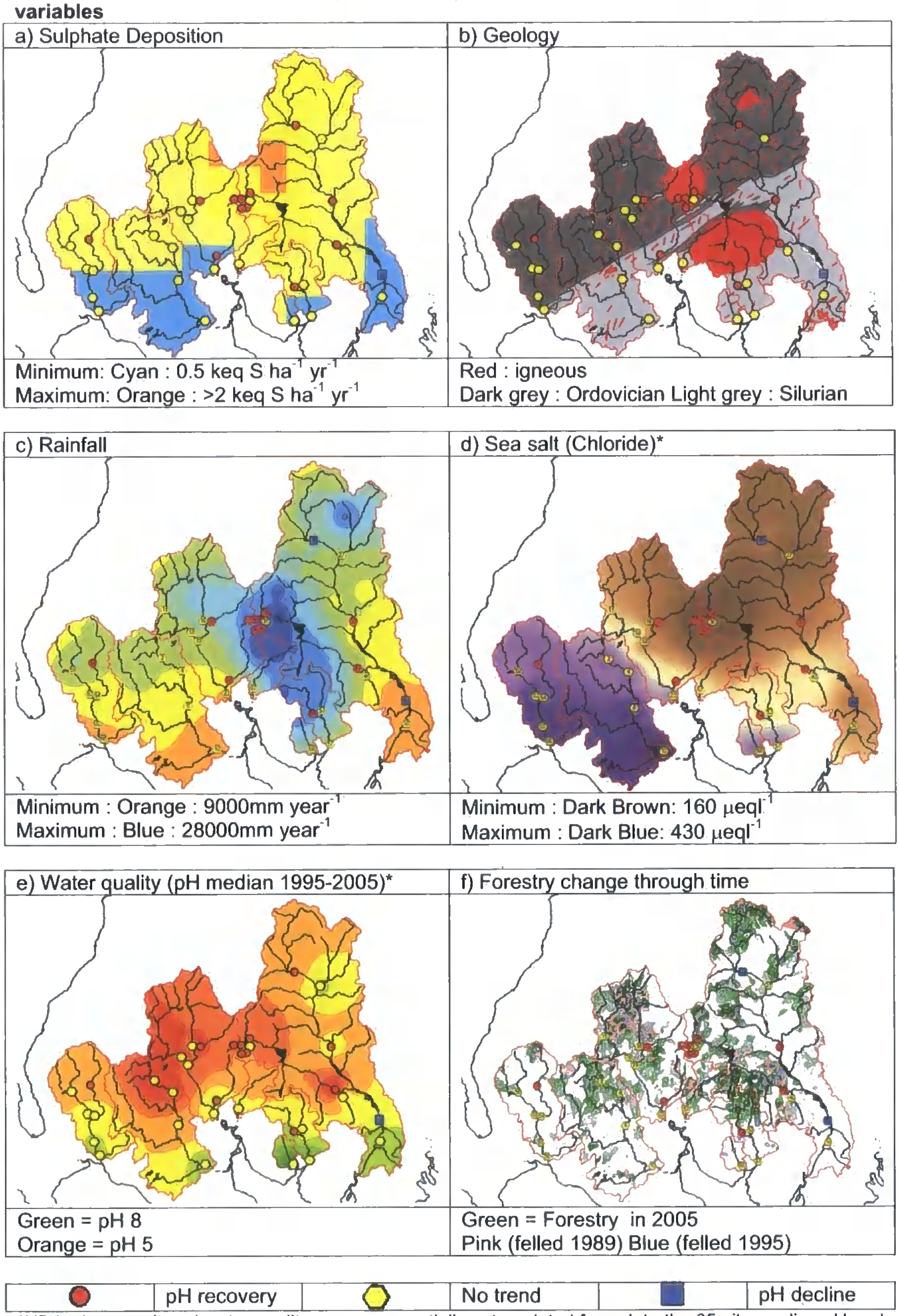
9.4.2a pH recovery variable

Analysis of spatial trends in pH recovery is limited by the data available. The regression coefficient of the recovery line cannot be used for an analysis of pH trends as it was in section 9.3.2 because only 12 of the available 35 sites show significant trends. Of these 12 trends a maximum of 7 were shown with any one summary statistic; too few for meaningful interpretation. Instead a binary variable of recovery presence/absence was generated, as shown in Table 9-2, where a site was allocated as having a recovery trend if a statistically significant trend at $P<0.05$ was identified in any of the four summary statistics.

9.4.2a(i) Catchment parameters

Five factors were identified as the most likely to contribute to pH recovery based on other scientific studies and trends observed within the data. These key factors were i) sulphate deposition, ii) geology iii) sea salt iv) antecedent water quality and v) forestry.

Figure 9-14 Regional distribution of pH recovery (in either central tendency or extreme) found through regression analysis of long-term SEPA data overlain on catchment variables



*NB both sea salt and water quality maps are spatially extrapolated from data the 35 site median pH and chloride data respectively. They are presented solely for descriptive purposes and are accurate only at the 35 site locations. This is particularly true for the water quality map which in reality is constrained by catchment boundaries.

9.4.2a(ii) Sulphate deposition

Change in sulphate deposition is likely to be the key driver behind recovery (Evans *et al.*, 2001; Davies *et al.*, 2005a). As demonstrated in section 9.3 the rate of freshwater sulphate recovery is directly related to the amount of sulphate deposited in 1995; average catchment deposition in 1995 is available for each site (6.5.4).

9.4.2a(iii) Geology

Geology, as a source of base cations and some acid anions to soils, can significantly impact recovery potential, as does the speed at which these ions are released. Furthermore, the previous chapter, and the work of Puhr *et al.* (2000) illustrates the influence of geology on the forest effect. The calculated catchment proportions of igneous and Silurian rocks are included. The Ordovician proportion is included by default as the difference between the other two. Whereas geology is a static variable, soil chemistry data would be a dynamic recovery variable that would help to better understand recovery patterns. However as it is not available Geology is used as a proxy representing the overall chemical vulnerability of a site.

9.4.2a(iv) Sea Salt

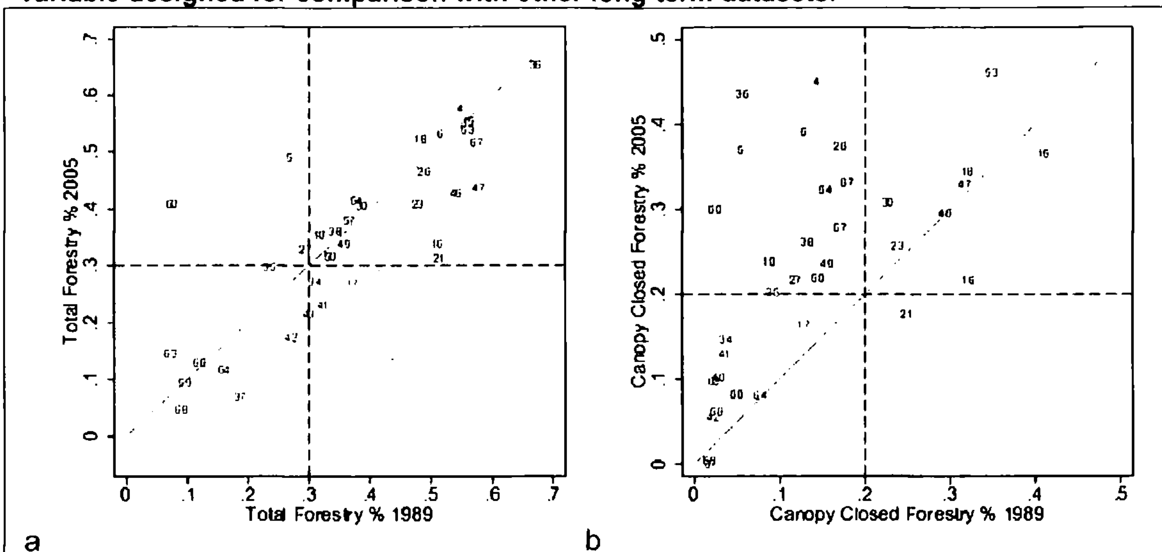
Sea salt has not been measured directly. Instead, three potential proxies are considered; these are site median sodium, chloride and Cl:Na ratio generated for the each site for the period 1995-2005, a period for which all sites have data.

9.4.2a(v) Antecedent water quality

Water bodies that have been had little sulphate deposition are far less likely to show a recovery trend than those which have been significantly acidified. Not all sites have data going back to 1980, and it is impossible to use regression estimates to predict pH for sites with missing data as the regression trends for some sites are not significant at $P<0.05$. Instead, as an indication of the overall water quality, minimum and median site pH for the period 1995-2005 were used.

9.4.2a(vi) Forestry Variables

Figure 9-15 Separating forestry into the TREECLASS variable, a long-term forest change variable designed for comparison with other long-term datasets.



Grey – small trees Green – mature forestry	Grey – non-forest Blue – establishing forestry Green – mature forestry Red – felled forestry

Table 9-8 The "TREECLASS" classes

Forestry	Code	Classification Rules
Non-Forest	1	CC2 <20% both years
Establishing	2	CC2 < 20% 1989, CC2> 20% 2005
Established	3	CC2> 20% both years
Felled	0	CC2 > 20% 1989, CC2 <20% 2005

The total proportion of catchment forestry (TF), and the proportion of canopy-closed forestry (cc2) for the years 1989 and 2005 were used as four site summary variables (TF_1989, TF_2005, cc2_1989 and cc2_2005). Figure 9-15 shows their distribution, and that, in terms of total forestry very few sites have changed in total proportion, whilst the changes in terms of the canopy-closed proportion have been more significant.

To create a categorical variable that took change in forest structure into consideration, a canopy-closed forestry proportion of 20% was used. This is lower than the 30% canopy-closed forestry proportion recognised by the Forestry Commission replanting policies as a) it was identified in the previous section that for the Galloway sites total forestry shows just as much correlation as canopy-closed forestry, and the sites identified as below 20% canopy-closed are below 30% total forestry, b) it was necessary to use canopy-closed forestry to provide an index of forest change and c) it was key not to underestimate the proportion of forest sites.

Sites were separated into classes of non-forestry (grey in Figure 9-15b), establishing forestry (blue), established forestry (green) and felled forestry (red) depending on the change in the canopy-closed proportion. This four-class ordinal variable is referred to as "TREECLASS" (Table 9-8). It should be noted that the class "felled forestry" contains a single site 21, the Penwhirn Burn in the Cree catchment; this site was removed from the analysis as the impacts of felling on recovery are not the focus of this study, rather the impacts of forest cover.

9.4.2b Exploring relationships between catchment variables

Figure 9-14 shows the maps that result from overlaying pH recovery on each variable, from these it is clear that there is a large amount of collinearity that results from spatial autocorrelation. As collinearity makes it difficult to differentiate the effects of one variable from another it is important to investigate the relationships that exist among all variables so that these relationships can be taken into consideration. This is especially relevant as the catchments studied have been selected for their availability of data, and not in a scientific manner that allows variations in one factor to be investigated whilst all others are held constant. As a result, collinearity between variables exists that makes the interpretation of the role of an individual variable difficult. In an attempt to compensate for this, principal components, scatterplot and correlation analyses are investigated to a) identify where the major sources of collinearity are within the dataset; b) determine to what extent interpretations of a forest effect on recovery can be separated from other impacts; and c) illuminate relationships between forestry and other variables once the major variations of the dataset have been taken into consideration.

9.4.2b(i) Identifying the major sources of collinearity

Forestry is not expected to be the major driving force behind acidification and recovery, instead it is expected to play a role that hampers recovery in areas where otherwise it would be expected. Principal components analysis is used here to a) highlight the variables contributing to the components that explain the greatest proportion of the variation within the dataset, and determine how these match with recovery b) determine the extent that forestry is separable from these major components in terms of collinearity and c) determine whether once these major factors are taken into consideration a forest impact on recovery can be identified.

Table 9-9 shows the first six components from a PCA of the 14 listed variables; combined these six components explain 93% of the variation within the dataset. These components can be roughly classed into geographical orientations and interpretations based on the factors that have the greatest correlations with them (Table 9-9).

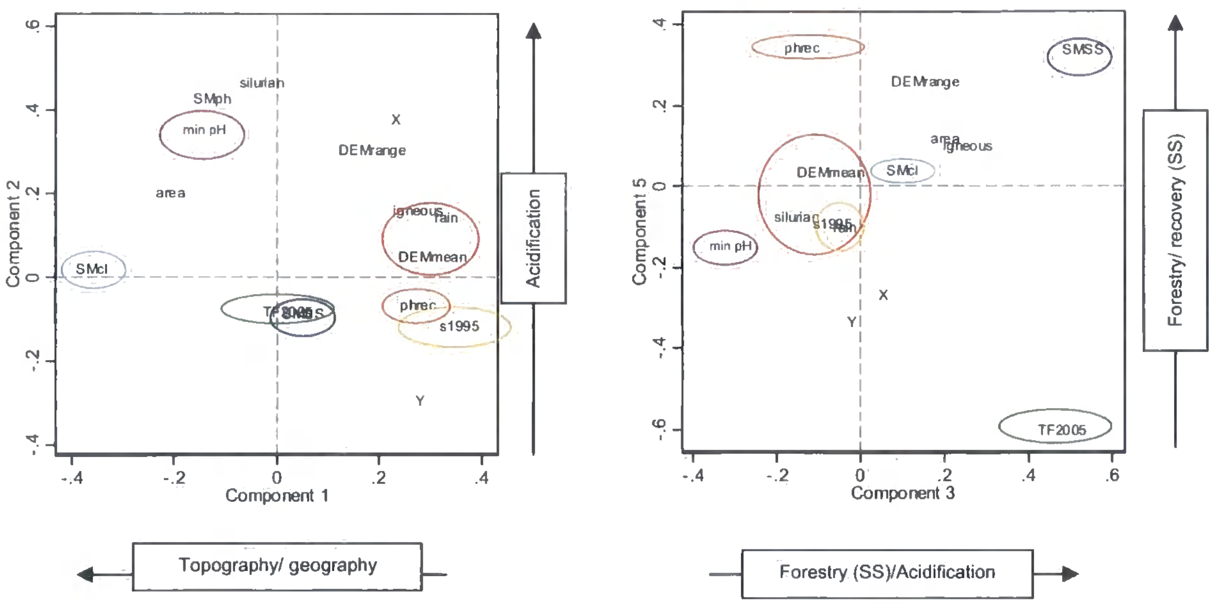
Neither the first nor the second principal components correlates strongly with forestry (|r|<0.05). Instead there is a clear group of catchment variables, correlated to easting and northing that drive the first 58% of the data without a forest influence. This is as expected and encouraging as it means that the forest component can be separated from this major axis, so that the collinearity within it does not confuse interpretation of any forest role.

Table 9-9 Principal components for the 35 pH recovery sites.

Component	**1**	**2**	**3**	**4**	**5**	**6**
Proportion	38%	20%	14%	11%	7%	3%
Eigenvalue	5.3	2.7	1.9	1.6	0.9	0.4
Interpretation	Geography/ Topography	Silurian/ High pH	Forestry/ pH	Topography/ Ordovician	Forestry/ Recovery	Recovery
Orientation	NE ➚	SE➘	-	N ↑	SW➘	(NE ➚)
Correlation Coefficients	**R1**	**R2**	**R3**	**R4**	**R5**	**R6**
pH Recovery Y/N	0.28	-0.03	-0.23	0.15	0.46	0.72
X	0.23	0.41	0.18	-0.04	-0.24	0.26
Y	0.28	-0.32	0.06	-0.30	-0.24	0.18
Rainfall	0.37	0.14	-0.13	0.28	-0.13	-0.21
Sulphate 1995	0.41	-0.12	-0.08	-0.05	-0.03	-0.13
Igneous %	0.27	0.20	0.13	0.40	0.10	-0.34
Silurian %	-0.03	0.50	-0.15	0.25	-0.17	0.27
Site Median Chloride	-0.41	0.02	0.04	0.16	0.07	-0.02
Cl:Na Ratio	0.05	-0.05	0.48	0.36	0.44	-0.05
Mean altitude	0.39	0.05	0.04	-0.31	0.06	-0.11
Altitude Range	0.18	0.34	0.29	-0.34	0.29	-0.16
Area	-0.21	0.24	0.38	-0.39	0.20	0.15
Minimum pH	-0.13	0.47	-0.32	-0.16	-0.08	-0.10
Forestry 2005	0.02	-0.05	0.54	0.19	-0.54	0.26

The autocorrelated variables that make up the principal component reflect a north easterly direction of decreasing salt deposition and increasing rainfall, altitude, sulphate deposition, and a larger proportion of igneous rocks. The second component reflects increasing proportions of Silurian geology, decreasing sulphate deposition and increasing minimum pH; it is also strongly spatially auto-correlated showing a south easterly direction. Figure 9-16a shows the loading plot for the first and second components; it should be noted that sulphate deposition and pH recovery plot very closely on both these components.

Figure 9-16 Loading plots showing the forestry-related components of PCA analysis for 30 SEPA long-term monitoring sites from which pH recovery data were calculated using regression analysis.



Variables

Phrec	pH Recovery Y/N
Min pH	Site minimum pH
TF_2005	Total Forestry (2005)
S1995	Sulphate deposition
Rain	Rainfall
DEMmean	Mean Altitude
DEMrange	Altitude range

Igneous	% geology
Silurian	% geology
SMSS	Na:Cl ratio
SMCl	Site Mean Chloride
X	Easting
Y	Northing
Area	Catchment area

Correlation and scatterplot analyses (Figure 9-17) reveal highly significant statistical (all $P<0.05$, most $P<0.001$) relationships between catchment variables such as sulphur deposition, rainfall, altitude easting and northing reinforcing the impression given by the first and second principal components of strong geographical autocorrelation between variables. This collinearity indicates that no one of these variables can be separated from the others in terms of determining which factor leads to recovery. Whilst it is likely that sulphate deposition is the key variable, the role of geology, sea salt or rainfall on modifying recovery potential cannot be determined due to the lack of control sites on geologies separate from sulphate deposition and sea salt effects. There is potential for the combination of datasets at a larger national/international scale to attempt to resolve these issues.

Evidence for pH recovery was shown to correlate significantly (at $P< 0.05$) with catchments with high sulphate deposition in 1995 ($r = 0.605$), low sea salt deposition ($r=-0.571$), high altitudes ($r= 0.529$), high rainfall ($r=0.496$) and that were further north ($r=0.448$) with smaller catchment areas (0.397) and greater proportions of igneous rocks (r=0.357). There was no significant (at P<0.05) correlation between forest cover in 1989 or 2005 and pH recovery.

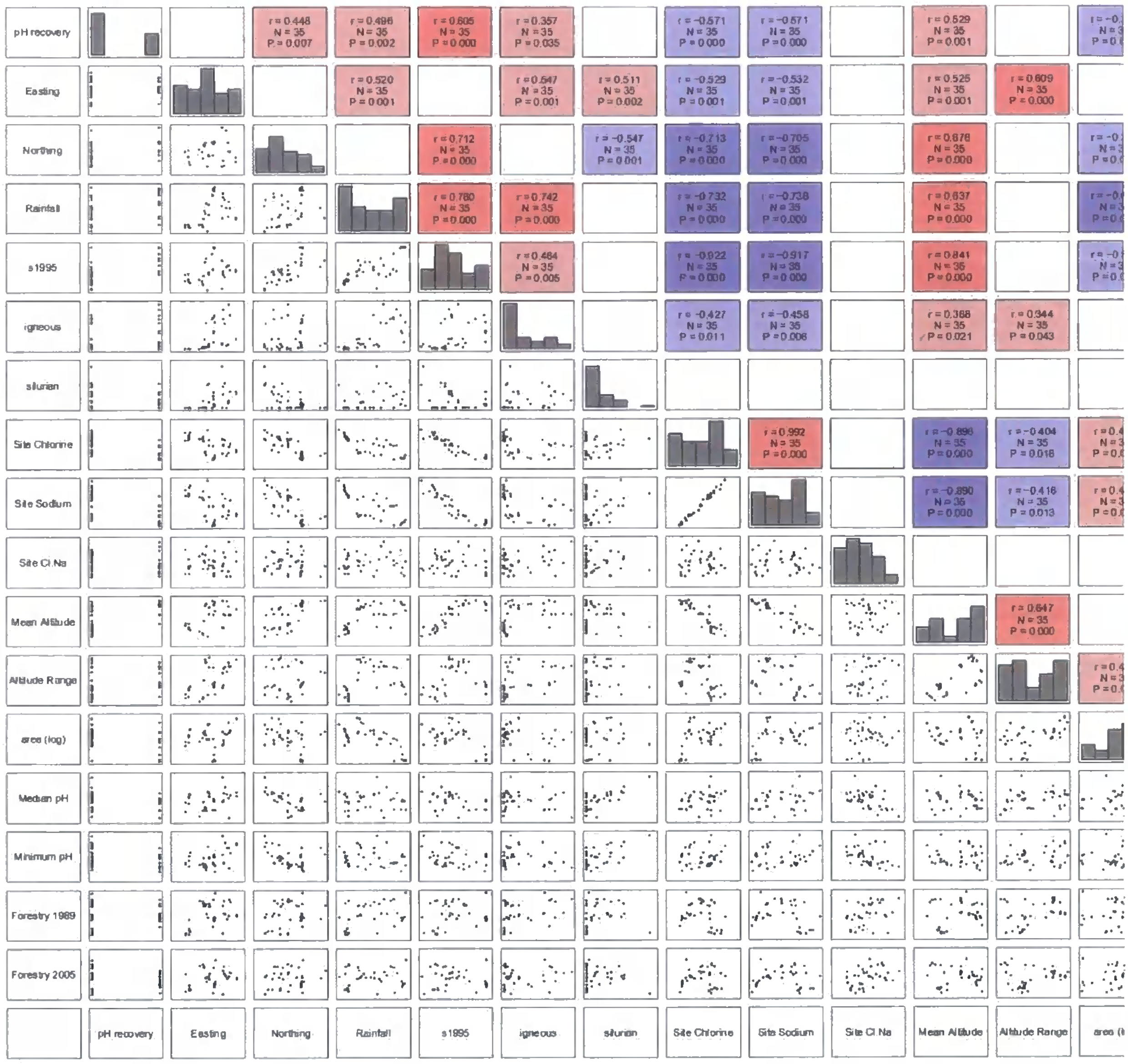
9.4.2b(ii) The role of forestry

The correlation and scatterplot matrix (Figure 9-17) shows forestry cover in 2005 to be independent of the major sources of multicollinearity within the dataset. It shows no correlations significant at P<0.05 with any of the auto-correlated variables (X, Y, rainfall, sulphate deposition, altitude). This is expected as it reinforces the findings of the PCA with the first and second components in section 9.4.2b(i). Instead, total forestry in 2005 shows a significant negative relationship (P <0.025, r=-0.387) with median pH, and a significant positive relationship (P<0.027, r=0.374) with Cl:Na ratio, indicating more chloride than sodium at afforested sites. There was, however, no significant (at P<0.05) correlation between forestry and recovery variables and it should be noted that the sodium chloride ratio is also shown to be independent of the major sources of autocorrelation.

Total Forestry in 1989 shows significant correlations with easting and the proportion of igneous rocks, reflecting planting prior to the Bladnoch's forestry reaching maturity.

The proportion of forestry in 2005 was shown to be independent of both of the two principal components within the dataset and all the auto-correlated individual variables. It does however have high eigenvectors with the third (0.54) and fifth (-0.54) principal components (see Table 9-9). These components, contribute significantly to the explanation of the overall dataset explaining 14% and 7% of the variation respectively. As indicated in Figure 9-16b the third component also correlates strongly with Cl:Na ratio (sites where there is more chloride in freshwaters than sodium) and a negative relationship with minimum pH (higher forestry, lower pH). This supports an interpretation of the third component as a forest effect on pH, with a potential sea salt scavenging driver.

Figure 9-17 Scatterplot and correlation matrix for pH recovery variables



The fifth component shows (see Figure 9-16b) a relationship between forestry (eigenvector -0.54) and recovery (0.46), with areas of low proportions of forestry cover showing higher recovery as well as elevated Cl:Na ratios. This suggests that the forestry/sea salt relationship shown to be related to minimum pH is not the factor relating forestry and recovery.

9.4.2b(iii) Relationships between variables: Conclusions

In conclusion, 58% of the variation within the dataset was shown to be driven by a north westerly trend of decreasing sea salt deposition, increasing altitude, rainfall, sulphate deposition sites with smaller catchments and increasing proportions of igneous rocks; forest cover in 2005 was shown to be independent of this major collinearity.

Furthermore, forestry was shown to be strongly related to the 3rd and 5th principal components which, combined, explain 21% of the variation in the dataset. This provides support for the hypothesis that there is a forestry influence on freshwater recovery. Whilst is important to remember that the fifth component does not represent forestry itself, but a variable in its own right that strongly related to both forestry and recovery, the existence of a component related to both forestry and recovery that explains a significant proportion of the dataset suggests that forestry's impact on recovery will be negative and cannot be ignored.

9.4.3 Multiple Logistic Regression Analysis

Logistic regression analysis was used to model relationships between raw catchment variables and recovery to determine statistically which factors are the most likely to explain the spatial pattern in recovery. All the variables explained in section 9.2.4 were used, and for categorical variables such as TREECLASS, binary dummy variables were created representing inclusion or exclusion in terms of each forestry class. Site 21, which changes forestry class from 1989 to 2005 due to felling, was excluded from analysis to minimise complications.

The results of logistic regression of pH recovery using one independent variable show the same order of variables as was shown by correlation analyses, with sulphate, sodium, chloride, altitude, rainfall, northing, catchment area and igneous rock proportion providing statistically significant models. As sulphate deposition is recognised to be the cause of acidification and its decline is expected to lead to recovery the fact that it provides the model which explains the greatest proportion of the variation within the data (c.37%) is not surprising. Unfortunately it is impossible to determine to what extent this recovery has been influenced by factors such as sea salt, geology, rainfall and altitude as PCA and correlation analyses indicated a large amount of collinearity among the other listed variables resulting from spatial autocorrelation.

Figure 9-18 Logistic regression of pH recovery

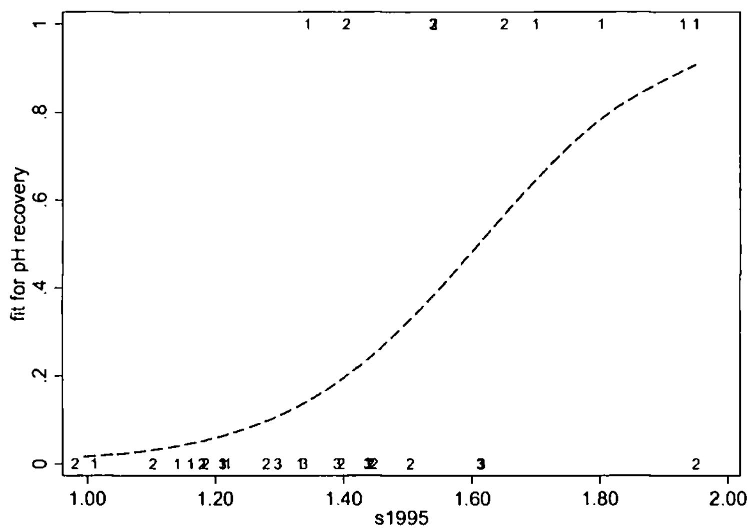
Variable	R^2	P
Sulphate 1995	0.3672	P<0.003
Site freshwater sodium	0.3194	P<0.002
Site freshwater chloride	0.3170	P<0.003
Mean altitude	0.2707	P<0.009
Rainfall	0.2035	P<0.009
Northing	0.1990	P<0.015
Catchment Area	0.1341	P<0.030
Igneous	0.1250	P<0.029
TC1 (Forest/Non-Forest)	0.1030	P<0.042
Easting	-	*P>0.05*
Ordovician	-	*P>0.05*
Silurian	-	*P>0.05*
SM_SS	-	*P>0.05*
Altitude range	-	*P>0.05*
Minimum pH	-	*P>0.05*
Median pH	-	*P>0.05*
TF_1989	-	*P>0.05*
TF_2005	-	*P>0.05*
TC2 (Establishing Forest)	-	*P>0.05*
TC3 (Established Forest)	-	*P>0.05*

The sulphate model has a standardised coefficient (z value) of 2.96 indicating a positive relationship between areas that had high sulphate deposition in 2005 and those with evidence of recovery. The model is highly significant, and explains around 37% of the variation in the freshwater pH recovery dataset.

Forest class is marked on the regression plot in Figure 9-19; it is notable that at high levels of deposition there appear to be more non-forested sites showing signs of recovery than afforested ones. This is reinforced to some extent as a model, statistically significant at P =0.042 exists between the forestry/non-forestry variable and pH recovery. This model has a standardised coefficient (z value) of 2.04 indicating a mild positive relationship between non-forested areas and recovery. The R^2 of 0.1030 is much lower than the sulphate based model (R^2 = 0.3672) indicating that forestry contributes to the explanation of a much smaller fraction of the variation of freshwater pH recovery (10%). It should be noted that neither TF_2005 nor TF_1989 produced a model for pH recovery significant at P<0.05.

As forestry was shown not to be strongly correlated with the majority of variables and the third and fifth components of the PCA suggested that that it may provide a secondary control once the impacts of other factors have been taken into consideration multiple logistic regression was explored. Adding forestry variables to an existing model based on the existing sulphate model added no improvements to R^2. Furthermore none of the added variables proved to be statistically significant at P<0.05 indicating that it is not possible within these dataset to show a statistically significant forest impact over and above the impact already explained by variations in sulphate deposition.

Figure 9-19 Logistic regression plot predicting pH recovery (trend significant at P<0.05; y=1) and non-recovery (y=0) by total S deposition. Sites are separated by forestry class (1 = Non-Forest, 2=Establishing forest 3= Established forest).



In spite of this, a simple plot of forestry against sulphate (Figure 9-20) shows that, though complex, a "forest effect" needs to be considered. It shows for the Galloway sites where sulphate deposition was low in 1995 there little evidence of recovery; no sites receiving less than 1.3 keq ha^{-1} year^{-1} deposition show signs of recovery. Similarly 7 of the 8 sites that received over 1.7 keq ha^{-1} year^{-1} sulphate deposition show signs of recovery in 2005. The complicating role of forestry is shown as no sites over 50% afforestation show signs of recovery, even the Green Burn (site 36) which received over 1.7 keq ha^{-1} year^{-1} sulphate deposition. The recovery of sites receiving medium levels of deposition under low to moderate levels of deposition are controlled by other factors in addition to forestry and sulphate, for example sea salt (Figure 9-21).

Figure 9-20 The relationship between total S deposition (keq ha^{-1} yr^{-1}) and forest proportion showing sites showing recovery in pH significant at P<0.05 (green) and those with no significant trends (red) for the 30 SEPA long-term monitoring sites for which long-term pH data are available. Numbers are site ID.

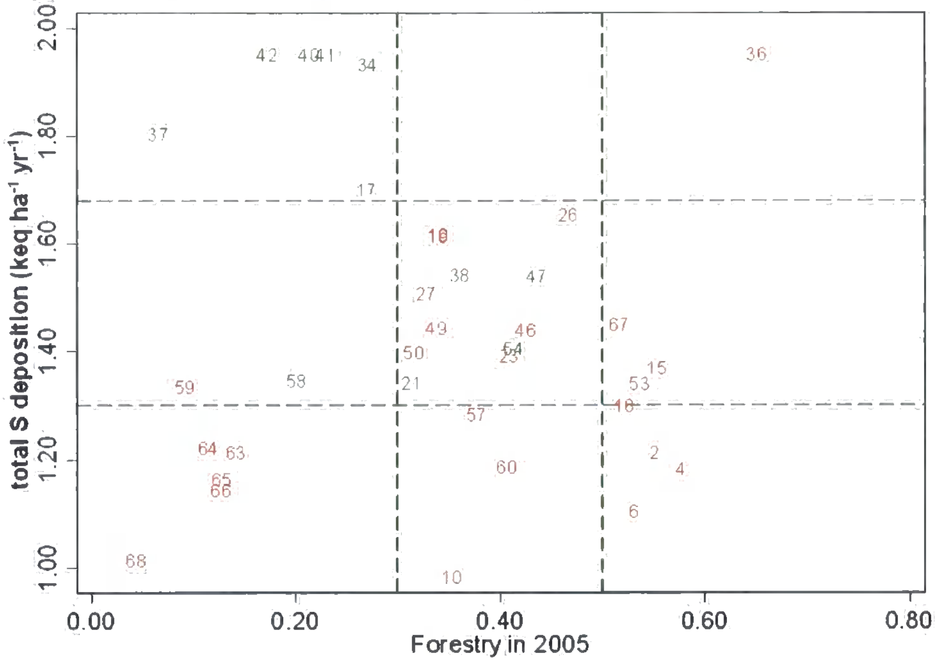
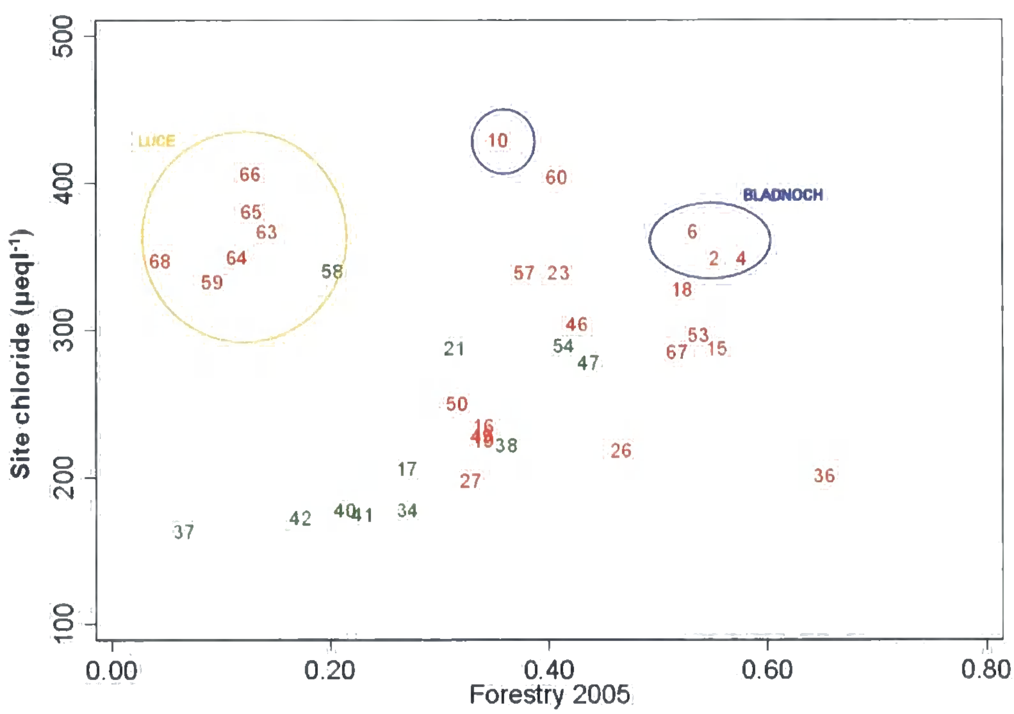


Figure 9-21 The relationship between forest proportion and site chloride (µeql^{-1}) showing sites showing recovery in pH significant at P<0.05 (green) and those with no significant trends (red) for the 30 SEPA long-term monitoring sites for which long-term pH data are available.



Careful forest management suited to specific catchment vulnerabilities is therefore suggested. Very little recovery is identified in either the heavily afforested Bladnoch or the moorland dominated Luce catchments, with only a single site in the Luce showing recovery despite both catchments receiving very low sulphate deposition levels and having pH levels below the median pH of the 35 sites. This suggests that another factor, potentially sea salt, is reducing their capacity to recover. As there is evidence that increased forest planting leads to positive trends in chloride scavenging (9.2.4b), if forestry is to contribute positively to meeting the aims of the WFD it must be carefully planned to minimise the exacerbation of existing water quality issues and encourage recovery.

9.5 Discussion

9.5.1 Findings in the context of National and International Literature

This chapter has presented a regional scale overview of recovery trends using an analysis of long term monitoring data held by SEPA. It takes a similar approach to the national scale analyses of the Acid Water Monitoring Network (e.g. Monteith, 2005; Shilland *et al.* al., 2007) and work at an international scale such as Stoddart *et al.* (1999), Evans *et al.* (2001) and Clair *et al.* (2007).

9.5.1a Limitations in trend analysis

It should be noted before discussing the trends identified, that any analysis of long term trends in water quality will also be impacted by changes external to the changes in sulphate deposition or forestry alone. Changes in the North Atlantic Oscillation are also known to take place, leading to inter-annual fluctuations particularly in sea salts (Hindar *et al.*, 2004), nitrate (Neal *et al.*, 2000), aluminium and DOC (Ness *et al.*, 2004) and as yet unknown changes in climate are thought to lead to increasing storminess making both acid pulse (Kroglund *et al.*, 2008) and sea salt (Laudon, 2008) extreme events more likely. These influences may mean that the failure to identify a trend is not in fact an indication of trend absence, but a result of inter-annual variations. Many studies use seasonal Kendall transformation (Hirsch and Slack, 1984) to correct for this, however this correction was not applied within the above analysis and so it should be noted that trend detection will be more sensitive to inter-annual factors such as the NAO. Furthermore, the number of sites available for analysis is not as large as would be ideal for multivariate analysis (32 sites for pH analyses; 20 for sulphate) and for some sites only very few determinants are available for analysis due to the data collection process. Nevertheless, it is greater than similar studies (Davies *et al.*, 2005; Larssen and Holme, 2006; Harriman *et al.*, 2003). The small sample size has restricted the analysis possible and should encourage a cautious interpretation of trends identified in the regionally distributed data.

9.5.1b Trends in freshwater sulphate (xSO_4)

Table 9-10 International trends in SO_4^{2-} 1990-1999 from Stoddart *et al.* (1999)

South/Central Ontario	-5.8*** $\mu eql^{-1}yr^{-1}$
North/Central Europe	-5.8*** $\mu eql^{-1}yr^{-1}$
Vermont/Quebec	-3.5*** $\mu eql^{-1}yr^{-1}$
Nordic countries	-3.1*** $\mu eql^{-1}yr^{-1}$
Midwestern North America	-2.6*** $\mu eql^{-1}yr^{-1}$
Maine/Atlantic Canada	-1.3*** $\mu eql^{-1}yr^{-1}$
Adirondack/Catskill mountains	-0.9** $\mu eql^{-1}yr^{-1}$
Great Britain	+0.0$^{n/s}$ $\mu eql^{-1}yr^{-1}$

Most apparent amongst the findings are trends in anthropogenic sulphate; of the 19 sites, 15 showed statistically significant ($P<0.001$) trends in median sulphate 1984-1998. The trends varied in strength between -1.50*** and -3.13*** $\mu eql^{-1}yr^{-1}$. Comparing these figures with the international scale trends identified by Stoddart *et al.* (1999; Table 9-10) shows the findings to be in line with expected trends of decreasing sulphate deposition of between 0.9 and 5.8 $\mu eql^{-1}yr^{-1}$ (1990-1999). It should be noted that Stoddart *et al.* (1999) found no significant downward trend in sulphate for the UK as a result of the influence of "*climatic variations, particularly as they affect the transport of sea salt aerosols across the region, rather than changes in anthropogenic emissions*". Evans *et al.* (2001) showed that for sites in mainland Europe (Italy, Slovakia, Czech Republic, Germany and Scandinavia) positive trends were common at 38 of 56 sites, with only the UK showing significant numbers (10 of 17) of sites with no trends significant at $P<0.05$ despite using seasonal Kendall corrections.

More recent work from the UK Acid Water Monitoring Network has updated this impression and shown that the majority of the UK's AWMN sites (18 of 22) show signs of reduced concentrations of freshwater sulphate. Davies *et al.* (2005) use seasonal Kendal to show sulphate trends in a range between +0.42* $\mu eql^{-1}yr^{-1}$ and -9.38** $\mu eql^{-1}yr^{-1}$ across the monitoring network. The three Galloway AWMN sites show very similar negative trends of a similar magnitude to this study (Round Loch of Glenhead, -1.88* $\mu eql^{-1}yr^{-1}$; Loch Grannoch, -2.71**$\mu eql^{-1}yr^{-1}$; see Davies *et al.*, 2005). It is fair to conclude that, where present, trends in freshwater sulphate in Galloway 1984-1998 fit with data available from national and international studies of sulphate deposition.

Table 9-11 Seasonal Kendall trends in AWMN data (1988-2003) significant at P<0.05 (*), P<0.01(**) and P<0.001(***). Green text denotes site > 50% forest; box highlights the three Galloway sites; modified from Davies *et al.* (2005).

Site	xSO_4^{2-}	NO_3^-	xCa+xMg	Alkalinity	AB-ANC	CB-ANC	H^+	Al_{lab}	DOC	Cl^-
	$\mu eq\ l^{-1}yr^{-1}$	$\mu eq\ l^{-1}yr^{-1}$	$\mu eq\ l^{-1}yr^{-1}$	$\mu eq\ l^{-1}yr^{-1}$	$\mu eq\ l^{-1}yr^{-1}$	$\mu eq\ l^{-1}yr^{-1}$	$\mu eq\ l^{-1}yr^{-1}$	$\mu mol\ l^{-1}yr^{-1}$	$\mu mol\ l^{-1}yr^{-1}$	$\mu eq\ l^{-1}yr^{-1}$
1 Loch Coire nan Arr									13.33**	
2 Allt a'Mharcaidh	-0.42**								6.67**	
3 Allt na Coire nan Con					1.32*				16.67**	
4 Lochnagar	-1.04**		-0.74*						5.83**	
5 Loch Chon	-1.46*			1.27**	2.70**		-0.17**	-0.49**	18.33**	
6 Loch Tinker	-1.25*								18.33**	
7 Round Loch of Glenhead	-1.88*			0.50**	1.54**		-0.38**	-1.35**	11.67**	-4.23*
8 Loch Grannoch	-2.71**		-1.50**		2.27**			-3.20**	14.17**	
9 Dargall Lane	-1.25**			0.67**	1.39**	0.86*	-0.17**	-0.56**	5.83**	-3.94*
10 Scoat Tarn			-0.95**		1.32**		-0.20**	-2.85**	6.67**	-3.10**
11 Burnmoor Tarn	-1.25**		-1.75*						10.83**	-5.63**
12 River Etherow	-9.38**		-6.82**		6.21**			-0.37*	35.83**	
13 Old Lodge	-9.17**		-2.48*	3.00**	7.01**	8.81**	-1.86**	-5.13**	32.50**	-10.42**
14 Narrator Brook	0.42*		0.38*	1.00*	1.19*				5.00**	-2.82**
15 Llyn Llagi	-1.67**		-1.05*	1.06**	1.95**		-0.39**	-0.62*	8.33**	
16 Llyn Cwm Mynach				-0.08**	0.87*				5.00*	
17 Afon Hafren	-1.04**		-0.65*						8.33**	
18 Afon Gwy	-1.67**				1.48*	1.95*	-0.12*		5.83**	
19 Beagh's Burn	-1.88**								40.00**	-3.66*
20 Bencrom River	-1.88**				2.25**			-1.50*	8.33*	
21 Blue Lough	-3.33**		-1.69**	0.81**	2.85**		-0.56**	-4.33**	11.67**	
22 Coneyglen Burn	-1.04*								42.50**	

The role played by forestry in terms of influencing trends of decreasing sulphate is harder to determine. Evans and Monteith (2000) compare trends in sulphate between mean forest and moorland sulphate and suggest that there is very little difference between forest and moorland sites in terms of sulphate trend. The findings of this study support this to an extent. Figure 9-9 suggests that freshwater sulphate trends, where they exist, are strongly related to 1995 sulphate deposition. From the 20 available sites it was clear that some of the most rapidly recovering are afforested. The sulphate scavenging mechanism (Mayer and Ulrich, 1974) is likely to explain this. Areas with high levels of forestry would be expected to capture more airborne pollutants; as such, they are likely to be amongst those with the highest sulphate deposition levels. Reductions in sulphate emissions should result in less scavenging (Figure 8-14) and so it is probable that these sites are seeing the greatest decreases in input will see the greatest response in terms of freshwater sulphate. This hypothesis is also put forward by Harriman *et al.* (2003) who identified similar findings: moorland streams in Galloway showed declines of -2 $\mu eq\ l^{-1}\ yr^{-1}$ compared to afforested streams that showed a greater -2.6 $\mu eq\ l^{-1}\ yr^{-1}$ decline.

Conversely, it is also notable that of the four sites failing to show recovery trends three are afforested despite. Recent AWMN reports shows similar findings, with negative trends in sulphate found at only 3 of the 5 AWMN afforested sites (Davies *et al.*, 2005 see Table 9-11). It is possible that under certain conditions the "forest effect" could be hampering freshwater recovery (Evans and Monteith, 2001). The factors that will determine whether or not the "forest effect" has an impact on sulphate recovery are likely to be the supply of base cations from weathering, or inputs of alternative anions for uptake within the soils (such as sea salt chloride, inputs of which will be increased by forest scavenging). These factors would influence whether or not sulphate is flushed to the rivers or retained within the soil, and, as a result, the extent to which forestry exacerbates trends in freshwater sulphate recovery (Evans and Monteith, 2001). There are, however, only four sites not showing signs of recovery and as such, conclusions are hard to draw. In terms of policy, the presence of high proportions of forestry in the only sites failing to recover from sulphate suggests a precautionary approach may be prudent. This is particularly important in light of the *Forest and Water Guidelines* since two of these sites are below 300m in the heavily afforested Bladnoch river basin.

9.5.1c Trends in acid recovery response variables

The majority of the analysis of recovery was restricted to trends in pH due to the availability of data. Far fewer recovery trends were identified in pH than were detected for xSO_4 with only 11 out of 36 sites showing positive trends. At a national and international scales, similar findings are identified by Davies *et al.*, 2005 and Evans *et al.* (2001). Davies *et al.* (2005) identified fewer trends in pH recovery than sulphate at 8 out of 22 (compared to 18/22 for sulphate) at UK AWMN sites and Evans *et al.*, (2001) identified 19 out of the 56 European monitoring sites (compared to 38 of 56 with sulphate recovery). This apparent discrepancy between sulphate and pH recovery is explained in part as a result of the fact that organic anions are produced as a by-product of recovery from acidification (Evans *et al.*, 2001; Monteith *et al.*, 2007). At many sites, positive trends in ANC show that mineral acids are declining, but organic acids increasing to take their place, evidenced by upward trends in DOC. This leads to a situation with no overall shift in pH, but in many cases an improvement in aluminium levels and ecological status (Davies *et al.*, 2005; Monteith *et al.*, 2007).

The data analyses within this chapter strongly suggest that sulphate deposition is the major driver of freshwater recovery (section 9-14; Figure 9-19) irrespective of a "forest effect" (Davies *et al.*, 2005). The analyses does, however, identify a statistically significant link between forestry and both pH and pH recovery using principal component's analysis as well as logistic and multiple regression approaches. Data trends fit with models of currently recognised mechanisms for a "forest effect" both in terms of the sulphate scavenging "forest effect" agreed within the *Forest and Water Guidelines* (Mayer and Ulrich, 1974; Fowler, 1989, FC, 2003) but also decreased availability of base cations due to forest uptake (Miller, 1981), and reduced availability of water for pollution dilution (Neal *et al.*, 1986). The findings are supported by the apparently slow recovery in the forested sites of the AWMN where four of the five afforested catchments show no positive trend in pH (Davies *et al.*, 2005; Table 9-11;

Monteith and Shilland, 2007). However, Harriman *et al.* (2003) also use collated long-term data from four regions, including Galloway, to quantify the "forest effect" on recovery. They note that forest lochs in Galloway show less pH improvement than moorland lakes, identifying only 3 of the 9 lochs in afforested catchments in Galloway as showing signs of recovery, whereas 8 of 10 moorland sites were. They conclude, however, that both forested and moorland lochs in general are recovering similarly in terms of SO_4, H^+ and aluminium. Harriman *et al.* (2003), however, used no multivariate analysis in their work to analyse pH trends, focussing instead on simple comparisons. Multivariate analysis, building on the dataset of Harriman *et al.* (2003) would be helpful as a way to evaluate the data further.

Furthermore, the work in this chapter stresses the potential for further analysis of the "forest effect" drawing on existing long-term datasets held by public bodies and research scientists. Many studies (Harriman and Morrison, 1981; Harriman *et al.* 2003; Ormerod *et al.*, 1989; Gee and Stoner, 1988; Davies *et al.*, 2005; Monteith and Shilland, 2007; Stoddart *et al.*, 1999; Evans *et al.*, 2001) indicate the availability of other long-term records which could be consolidated to widen the number of forest and moorland sites available for study. These data could then be combined with land use (especially forestry) proportions extracted from satellite imagery (Dunford and Donoghue, 2007); information on base cation availability from soil or geology maps (e.g. BGS, 2007) and modelled sulphate deposition data (e.g. Dore *et al.*, 2007; Fowler *et al.* 2004) to extend the analyses presented here. Issues of comparability between surveys (e.g. high flow/ median flow, see 6.2) would need to be considered but a large dataset would provide the potential to further control for the spatially distributed factors that lead to a "forest effect", and determine the extent to which the findings identified in Galloway are identifiable elsewhere.

9.5.1d Loch Dee work

The findings of this thesis also update work begun with the Loch Dee project that has been the subject of ongoing research since the early 1980s (Burns *et al.*, 1984; Langan, 1985; Welsh and Burns, 1987; Flower, 1992; Harriman and Langan, 1992; Langan and Harriman, 1992; Nisbet *et al.*, 1992; Shaw, 1992; Welsh, 1992; Lees, 1995; Nisbet *et al.*, 1995; Langan and Hirst, 2004). The Loch Dee sites are the only sites within this project for which there is sufficient data to identify negative trend in critical load exceedance and a positive trend in Charge Balance ANC. These trends are clear indications of chemical recovery that are evident in spite of a lack of seasonal correction, and in spite of the influence of maritime conditions on sea salt deposition that hampered trend detection in the UK for Stoddart *et al.* (1999). With the exception of the Green Burn (discussed below), negative trends in sulphate deposition are matched by a positive trends in pH (at $p<0.05$). Reports from the 2007 AWMN review (Monteith and Shilland, 2007) demonstrate that the Dargall Lane (the Loch Dee project's moorland catchment) also shows depletion in labile aluminium and that flora and macroinvertebrate fauna have begun to show early signs of biological recovery. This evidence for freshwater recovery at the Loch Dee sites makes it clear that recovery from acidification is beginning to take place in some locations within the Galloway area. This in turn encourages a focus of research on those areas where this recovery is taking place so as to determine the factors hampering this process. The absence of matching trends in pH and freshwater sulphate at other sites in the region stresses that the Loch Dee data cannot be used as a worst case scenario for Galloway, despite the igneous rocks on which they lie. Less acid-sensitive Ordivician bedrock areas such as the Cree, Bladnoch and Luce still fail to show no signs of pH recovery. Whilst this may be due to the greater influence of the NAO and/or sea salts affecting trends (Hindar *et al.*, 2004) or trend detection (Stoddart *et al.*, 1999) in these more coastal regions it serves as a clear reminder that the western catchments may be areas of concern. This is particularly significant as none of these western areas are highlighted by the *Forest and Water Guidelines* (Cf. Figure 7-8) Critical Loads model or 300m rule.

It should also be noted that, in contrast to the other Loch Dee sites, the afforested Green Burn shows no trend in pH. This difference was first noted by Langan and Hirst (2004) using 1989-2000 data. This thesis demonstrates that an additional six years of data does not change the trend. It is therefore fair to argue the Loch Dee project's Dargall Lane/ Green Burn data as a long-term paired catchment providing evidence in favour of the existence of a long-term "forest effect" on recovery. It should be stressed, in the light of this, that the Green Burn catchment would be excluded from sensitive forest management under the *Forest and Water Guidelines*: the majority of the forestry within the catchment is below 300m (see Figure 4-5). As a result the Loch Dee project stands as a further reminder that the 300m guideline needs to be reconsidered.

9.5.1e Ecological impacts

The data presented within this chapter focuses on indications of recovery in freshwaters. It should, of course, be recognised that ecological recovery is not a foregone conclusion, even when signs of chemical recovery are apparent (Monteith *et al.*, 2005), a fact that is particularly significant if the aims of the WFD are to be met (Jenkins *et al.*, 2003). There has been some evidence for ecological recovery in some previously acidified regions of Scandinavia since the early 2000s (Skjelkvale *et al.*, 2001; Kroglund *et al.*, 2001; Nyberg *et al.*, 2001). In the UK, Recent AWMN research (Monteith *et al.*, 2005a) shows that "subtle ecological improvement" is present at sites showing chemical improvements. In terms of a "forest effect", very few studies have focused on questions of ecological recovery of forest sites specifically. However, the five afforested sites within the AWMN give tentative indications that ecological recovery may well be possible, mainly due to decreasing aluminium concentrations, but that widespread recovery is far from commonplace (Monteith and Shilland, 2007). The noted trends are as follows: *Allt na Coire nan Con* shows no pH trend but signs of reduced aluminium and "gradual establishment of some acid sensitive macroinvertebrate species"; *Loch Chon* shows marked pH and Al trends and shows recovery across a variety of sensitive species; *Loch Grannoch*, shows declines in Al but levels remain high enough to be toxic to fish, it shows no signs of biological recovery; *Llyn Cwm Mynach* shows little indication of any change in pH but some drop in Al matched by some subtle improvements in epilithic diatom flora whilst *Afon Hafren* shows signs of Al decline and an increase in acid sensitive stoneflies (Monteith and Shilland, 2007). Both Afon Hafren and Loch Grannoch are however noted as very vulnerable to sea salt events which are capable of "raising aluminium concentrations above severely toxic levels" (Monteith and Shilland, 2007). With the increased sea salt scavenging exacerbated in forest sites as highlighted in the previous chapter (and Larssen and Holme, 2006) the Forestry Commission cannot consider the "forest effect" a thing of the past. Unfortunately without information on trends in aluminium it is difficult to further interpret the ecological impact of the findings in this chapter beyond the recognition that the sites with increasing pH are more likely to recover than those where no recovery trend is yet detected.

9.6 Conclusion

In conclusion, it is suggested that changes in sulphate deposition are the primary drivers of freshwater recovery. However, there is sufficient evidence for a "forest effect" on recovery (summarised in Table 9-12), that further research should be targeted at better identifying the mechanisms by which this effect is takes place. With regard to the *Forest and Water Guidelines*, it is clear that the assumption that the "forest effect" is well understood (Chapter 7) and that the *Forest and Water Guidelines* are sufficient to identify the sites at risk, requires considerable reconsideration in the light of the findings of both this chapter and Chapter 8. Chapter 10 reflects on the thesis as a whole and summarises Best Available Knowledge drawn from its findings, the factors that have influenced the transfer of this knowledge and suggests further directions for policy, practice and research.

Table 9-12 Summary of forest impacts on long-term trends	
•	The four sites showing statistically significant increases in freshwater chloride 1995-2005 all also showed evidence of forest growth 1995-2005
•	The one site showing statistically significant negative trends in freshwater chloride 1995-2005 also showed evidence of felling 1995-2005
•	Of the four sites not showing evidence of a statistically significant sulphate recovery three were afforested.
•	Both of the sites showing statistically significant negative trends in pH are over 30% afforested.
•	The forested site of the loch Dee project is the only one not showing evidence of a statistically significant pH recovery.
•	The fifth principal component, explaining 6% of the variation within the 35 site dataset relates strongly to both forestry and pH recovery.
•	Logistic regression to estimate pH recovery likelihood using Forestry/Non-Forestry produces a statistically significant result ($P<0.05$, $R^2=0.10$).

Chapter 10 : Synthesis and Management Recommendations

10.1 Introduction

The aim of this thesis has been to develop a holistic understanding of ***the factors that influence the extent to which environmental policy and practice are founded on the Best Available Knowledge of the environment***. The study has focused on investigating the role of knowledge in decision making and the process by which different knowledges are included and excluded from the decision making process.

"Best Available Knowledge" has been defined as: *the theoretical holistic state of knowledge which results from the evaluation of multiple stakeholders' knowledges (whether expert, scientific, lay or local), and the best available scientific data regarding the issue.* In drawing the thesis to a close this section synthesises the findings of the spatial and statistical analysis chapters 7, 8 and 9 in the light of the varied stakeholder knowledges identified in chapters 3, 4 and 5 to conclude with a summary interpretation of Best Available Knowledge of the ""forest effect". The chapter then addresses the thesis aim and identifies the factors that have influenced the extent to which Best Available Knowledge of the "forest effect" is incorporated in forestry policy and practice.

In doing so the chapter addresses the research questions set out in Chapter 1:

- What is the Best Available Knowledge about the "forest effect"?
- What factors influence the extent to which Best Available Knowledge of the "forest effect" is incorporated in *forestry policy*?
- What factors influence the extent to which Best Available Knowledge of the "forest effect" is incorporated in *forestry practice*?

The chapter concludes with a reflection on the challenges of environmental management and puts forward management recommendations for a fifth version of the *Forest and Water Guidelines*.

10.2 Best Available Knowledge

Before considering what the Best Available Knowledge collated by this study is, it is important to consider to what extent the findings presented here really represent Best Available Knowledge of the "forest effect". It should be recognised that "Best Available

Knowledge" would be a bold claim to make; there will always be other views to include and more data to collect. Instead when this thesis refers to "Best Available Knowledge" it really refers to "Better Available Knowledge"; "better" than that presented by any one view of the environment alone. The thesis is founded on the belief that, by gathering an understanding of the relationships between stakeholders, the knowledge they use to make their decisions and the institutions within which they belong and a more rounded and informed understanding of the issue can be created.

Section 10.2.1 synthesises the findings of this thesis by providing bullet-point summaries to the following key questions:

- Is there evidence of a "forest effect" despite the 70% SO_4 deposition reduction?
- Where does the "forest effect" exist and whose "forest effect" is it?
- What is the mechanism for the "forest effect"?
- Is there evidence for a "forest effect" on recovery?

10.2.1 Best available knowledge of the "forest effect"?

10.2.1a Is there still a "forest effect" despite the 70% SO_4 deposition reduction?

- **Yes.**
- A "forest effect" on pH is identifiable in 2005 high flow data as well as SEPA's median flow samples in 2003 and 2005.
- A "forest effect" of decreased charge balance ANC, and increased sulphate, chloride and sodium is clear at high flow in 2005 and 2006.
- These fit with the "forest effect" identified in the 1980s and 1990s (Harriman and Morrison, 1982; Stoner and Gee, 1985; Ormerod *et al.*, 1989; Puhr *et al.*, 2000) despite 70% decline in sulphate deposition.
- This is not detected for pH in 2006, suggesting the continued importance of individual extreme events (Laudon, 2008).
- The magnitude of the effect may have decreased, particularly in terms of alkalinity and sulphate; however variation between events makes comparisons of magnitude difficult.
- For sites under 300m the impact on pH with an increase in forestry from 0 to 100% of the catchment is -1.2 pH units in 2005 and -0.9 in 2006 on high flow pH and -1.2 pH units in 2003 and -1.8 in 2005 on median flow pH (Table 8-10).
- There is considerable scatter around the regression lines (R^2<0.3), as would be expected with the number of other variables involved; nonetheless the relationships are statistically significant at P<0.05.

10.2.1b Where does the "forest effect" exist and whose "forest effect" is it?

- **The "forest effect" matches well with the wider "forest effect" identified by local stakeholders in the lowland Ordovician sites in the Bladnoch and Cree in addition to the acid-sensitive catchments of the Dee and Fleet.**
- The "forest effect" is identified on Ordovician and Igneous rocks both above and below 300m.
- For Silurian geology sites there are too few data to be able to comment confidently although some trends are apparent. It should be noted that as pH is higher in these sites, the ecological impacts are less likely to be significant than in the more acid-sensitive areas.
- The "forest effect" does not match well with the mechanism-down view of the "forest effect" represented in the *Forest and Water Guidelines*.
- The "forest effect" exists below 300m: removing sites with forestry above 300m makes no difference to the existence of relationships between forestry and water chemistry at lower altitudes.
- The "forest effect" is not identified by the Critical Loads model: whilst other water quality variables (pH, SO4, ANC, Cl, Na etc.) show relationships with forestry, the Critical Loads model does not.
- The Critical Loads model for 2005 and 2006 identifies areas of acid sensitivity that match primarily with local igneous geology: it does not identify many other areas e.g. Ordovician rocks.
- Increasing the ANC to 20 increases the number of sites that exceed the critical load. However, large areas of the Bladnoch and Cree remain classified as "not at risk". It does not appear that modifying the ANC limit will help identify the wider "forest effect" using this approach.

10.2.1c What is the mechanism for the "forest effect"?

It should be noted that the identification of the mechanism for the "forest effect" was not the aim of this PhD; however, some suggestions regarding potential causal factors are identified below.

- **We cannot be certain; more research is needed.**
- The long-term nature of the problem in the face of sulphate deposition decline and its existence in low-altitude sites suggest that scavenging of anthropogenic pollution may not/no longer be the most important "forest effect".
- It is also possible that the cloud base in Galloway is lower than expected and the 300m rule misrepresents this in policy.

- Scavenging may still have a role to play in terms of capturing sulphate, nitrogen compounds (NO_x) or sea salts but in addition alternative mechanisms (DOC release, base cation uptake, soil drying etc.) should be explored.
- During sea salt events (such as 2005 high-flow data) forest scavenging appears to introduce an anion bias in the chloride:sodium balance; this may contribute to acidification in sensitive areas (section 8.6.2).
- On Ordovician geology DOC release increases shows statistically significant relationship with forestry in 2005 and an increase of DOC in the order of $\approx$10mg l^{-1} with increase in forest cover from 0-100% (section 8.6.5).
- The changes in DOC may reflect the findings of Monteith *et al.* (2007) who link DOC increase to recovery from acidification; forested areas with a greater acidification history may be responding by generating more DOC. Further research is required, but whatever the case, increased DOC under forestry will provide acid anions and reduce the recovery potential of afforested streams.
- Further research is needed to identify whether the extent to which the "forest effect(s)" identified here are identifiable in other areas; the focus on acid deposition alone may mean that acid problems in other areas may not have been identified.

10.2.1d Is there evidence for a "forest effect" on recovery?

- **Yes, some.**
- The decrease in sulphate deposition is the factor most responsible for recovery.
- Of the Loch Dee sites, only the afforested Green Burn shows no increase in pH 1980-2005.
- This and evidence from PCA analysis and comparison of non-recovering sites adds further weight to a "forest effect" on long-term trends as suggested by other studies (Helliwell *et al.*, 2003; Davies *et al.*, 2005b)
- Statistical analysis is, however, hampered by the number of long-term monitoring sites available.
- This evidence could be strengthened with reference to long-term datasets from other acidified regions (e.g. Wales).

10.2.2 Summary

10.2.2a Best available knowledge of the "forest effect"

Based on the preceding evidence, my interpretation of Best Available Knowledge is as follows:

Best Available Knowledge of the "forest effect" is that suggested by local stakeholders: a wider "forest effect" than that found in the *Forest and Water Guidelines*. The "forest effect" is not restricted to upland catchments, nor is it restricted to areas of Critical Loads exceedance: the effect is present in the lowland catchments of the Luce, Bladnoch and Cree in addition to the more acid sensitive catchments of the Fleet and Dee. Furthermore, it seems likely that there is a "forest effect" on long-term recovery of water bodies.

Most importantly, however, it is clear from Best Available Knowledge that the exact mechanism for the "forest effect" is not as well understood as it is represented in policy: it cannot be claimed to be any "known" or "agreed" mechanism without further research.

I would like to stress that this is not a view that I have reached lightly; my own stance regarding the wider "forest effect" has fluctuated significantly during the learning process as a result of literature review, communication with stakeholders, and analysis of data. It was the analysis in Chapters 8 and 9 that helped me to reach the views expressed above.

10.3 The factors affecting Best Available Knowledge

The previous section defined Best Available Knowledge of the "forest effect". This section answers the second and third research questions raised in Chapter 1: "what factors control the extent to which Best Available Knowledge is included in forestry policy and practice?". The factors identified by this thesis are summarised below along three key themes: the privileged role of Science (10.3.1), managing a complex environment (10.3.2) and the importance of inter-stakeholder relationships (10.3.3).

It is appreciated that deconstructing someone else's interpretation of the environment is much easier than constructing your own and the management recommendations that follow in section 10.4 are an attempt to redress this.

10.3.1 Privilege given to a subjective Science

The privileged position given to Science by stakeholders has been shown to have a significant impact on the extent to which management of the "forest effect" (both in policy and practice) has been able to follow Best Available Knowledge. For policy makers "Best Available Science" has been used as a means of legitimising the choices present in the *Forest and Water Guidelines*, a means of defending decisions in the face of the opposing views of private foresters and fisheries interests (chapter 3). For forest managers the *Forest and Water Guidelines* are rules for forest practice that present a "Best Available Science" that, although they do not have any specialist knowledge of it, they trust as it is agreed by the scientific experts who designed the guidelines.

This privileged position implies that the Science that is playing the role of mediator in disputes is a) objective b) politically neutral and c) infallible. As discussed in Chapters 1 and 2 social constructivists argue that this is a condition that is never the case, that Science is just as "*socially grounded, conditional and value laden*" (Wynne, 1992) as any other way of knowing. The findings of this thesis reinforce these conceptions; the following sections draw examples from the thesis as a whole to illustrate how the way that Science is conceived remains a significant factor that restricts access to Best Available Knowledge in Science itself, Policy Making and Practice.

10.3.1a Science as subjective and fallible

In Chapter 2 the work of Latour and Woolgar (1979) was used to demonstrate the significance of the technical matters that are "taken for granted" during the scientific approach but which are vital to the process of fact creation. These points are especially relevant as the data discussed contribute to decision making. The bullet points below highlight five examples from this thesis which illustrate the importance of recognising the importance of these technical matters as the context that frames that scientific "facts" and illustrate that science itself is subjective and fallible.

- **Laboratory Methods:** The issues surrounding the inter-laboratory tests for sulphate (Chapter 6) are a clear example of the importance of context: if the laboratory method is not designed to identify the target variable it will be unreliable. This problem is a far more understandable complication than it sounds; a laboratory needs to know the use to which the samples it analyses are going to be put to select the appropriate analytical method and the interpreter of the results needs to be aware of the limitations of the analytical procedure and laboratory methodology applied. These issues are not always given the prominence they deserve.
- **Selection of Models:** The same principle applies to model selection; the *Forest and Water Guidelines* Critical Loads model in its current form is inappropriate as it does not match the "forest effect" it is trying to test (10.2.1b).
- **Location of Monitoring sites:** The location of monitoring sites constrains what can be known. In Chapter 5 the GFT discussed the impacts that this could have for the classification of a river and therefore the management (and even recognition) of a risk. These issues become particularly important for monitoring long-term trends as once selected, moving a site requires re-starting the record.

- **Interpretation of data:** As the GFT demonstrated in Chapter 5 for data to be well used it needs to be understood in context; some expert knowledge is therefore needed – furthermore different interpreters will interpret the same data in different ways (see 5.3.1a(ii)).
- **Combining data:** There is a significant amount of data available that has been untapped as a means to answer pertinent questions raised by the environmental issues. Simply collecting and archiving data is not sufficient; there is significant potential for datasets such as the Loch Dee record, SEPA long-term records and datasets like them to be better exploited to contribute to Better Available Knowledge. Remote Sensing also has a role to play as a source of information.

10.3.1b Science in policy and practice

The bullet points below illustrate ways in which the technocratic viewpoint of the *Forest and Water Guidelines* and the belief that the Science represented in policy was the only "forest effect" prevented the Best Available Knowledge of the "forest effect" held by local stakeholders from being included in policy and practice.

10.3.1b(i) Forestry Policy

- **Hard-line Realist Epistemology:** The Forestry Commission have taken the view that "Best Available Science" can be used alone to mediate in debates (Chapter 3) taking a strong line on the importance of scientific proof (Chapter 3). Although consultation is included in the creation of the *Forest and Water Guidelines,* the risked based approach in the 4th edition is strongly based in Science. The belief that science can be used in this way is flawed for the following reasons:
    - Privileging "Scavenging": Once scavenging was agreed as the "forest effect", it became the only "forest effect" controlled for in the guidelines. The potential for a wider "forest effect", and thus the possibility of wider knowledge, was dismissed as a result.
    - Exclusion of local/lay knowledge: fisheries viewpoints were fought against using demands for scientific proof (Chapter 5), rather than sufficiently explored to identify the existence of wider problems.
    - Selection of science: Some scientific evidence suggesting a wider "forest effect" existed and was not included by the guidelines (Chapter 4); the Critical Loads approach is inappropriate for a wider "forest effect", as is the 300m rule.
    - Uncertainty of science: It is still unclear as to what the exact nature of the "forest effect" is and how exact management guidance can be

related to chemical and environmental impacts. This uncertainty is discussed in more detail in section 10.3.2.

10.3.1b(ii) Forestry Practice

- **Precautionary Approach:** Forest practitioners are less constrained by the realist scientific viewpoint and are more willing to follow a precautionary approach and go "beyond the guidelines". This contributes positively to the ability of forest practice to include Best Available Knowledge.
- **Belief in science:** Forest practitioners are not scientific experts and may take the evidence provided to them by scientists at face value (Chapter 4); they may not argue with this science even when it does not match their understandings of risk. This prevents them from taking full benefit of their greater access to Best Available Knowledge provided them by their network relationships with other local stakeholders (Chapter 5).

10.3.1c The conception of Science as a factor influencing the inclusion of Best Available Knowledge

The role given to science and its perception by stakeholders is therefore a key factor that impacts the extent to which both policy and practice have the ability to be based on Best Available Knowledge. Better Available Knowledge is enabled by viewing science as one of many possible ways of knowing, as subjective, fallible and human-created way of understanding the environment; a way of knowing that if used wisely in conjunction with other forms of knowledge can lead to both policy and practice more closely incorporating Best Available Knowledge. These findings fit with the expectations raised by the social constructivists who stressed the relationship between knowledge and power and how, by defining a problem, individuals can be restricted in terms of how it is possible to approach that problem (Foucault, 1980). Similarities with Wynne's (1992) case study of Cumbrian sheep farmers are also apparent; he also demonstrated how, relevant local knowledge was ignored by scientists who were demonstrated to have used inappropriate science (Wynne, 1992; see Chapter 2).

10.3.2 Science to manage a complex environment

In Chapter 1 integrated catchment management was introduced as a complex problem around a common pool resource (Ison *et al.*, 2007). This complexity is enhanced by uncertainty surrounding the best management of the issue and the number of stakeholders with competing claims and different views of how the issue should be best managed (Blackmore, 2007). The key issue was subtractability, where meeting the needs of one user reduces the benefits of another. Decision makers therefore need to recognise this complexity and realise that rather than a scientific problem to solve: environmental management is a "*resource dilemma*" (Ison *et al.*, 2007) where no one solution is good for all. By using Science as the decision making tool (as discussed above) policy makers gloss over these complexities and present environmental management as a question to which there is one single answer that can be achieved by the application of science.

The sections below draw examples from this thesis to illustrate the ways in which the belief that the problem can be resolved by Science prevents Best Available Knowledge being integrated in policy and practice.

10.3.2a Problems beyond science

The following examples illustrate the external considerations beyond objective science that decision makers need to consider in addition to Best Available Science when making decisions.

10.3.2a(i) Considerations for "doing" science

- **Cost of data collection/analysis:** Data collection costs money, these costs may be even higher if data are privately collected and need to be purchased (Cf. GFT Chapter 5). The cost to buy these data and willingness to share/pay are therefore factors that contribute to whether or not data are available as a source of knowledge to decision makers. Similarly, the financial support and time for analysis are vital as otherwise the time/effort/money put into data collection is wasted. Institutional factors such as trust and collaboration (see below) can help to mitigate (or aggravate) the impacts of some of these factors. With regard to long-term monitoring the maintenance of continued funding is also critical, and sustaining interest and financial support raise challenges themselves.

10.3.2a(ii)Problems for Policy

- **Pragmatic Concerns:** It is needless to apply the *Forest and Water Guidelines* for acidification to the whole forest estate. As a result the Forestry Commission has used risk-based approaches such as the 300m and restocking/replanting rules to determine areas for more sensitive forest management (Chapter 3, 4). These approaches do not match Best Available Knowledge of the "forest effect"; as a result the need for their use, and the approach selected are both factors that restrict the decision maker's access to Best Available Knowledge.

- **Regional Scale:** The "forest effect" on acidification is a significant issue for Galloway but not for the UK as a whole. This is a factor that affects its prominence as an issue for SEPA to address (Chapter 4).
- **The uncertain "forest effect":** The "forest effect" itself ultimately determines whether or not any change in policy (or practice) has the desired effect on the environment. As the mechanism for this is unknown (10.2.1c), it is difficult to predict what level of remedial action will be effective. Recovery of fish in the upper Cree following felling (Chapter 7) suggests that removing trees may be effective; re-planting these areas may counteract this: we do not know. This representation of the "forest effect" as a problem to which the answer is known in the *Forest and Water Guidelines* discourages precautionary approaches in areas outside of those identified as at risk by the guidelines.
- **The diffuse pollution challenge:** Before the WFD there was no environmental legislation to properly address diffuse pollution; with the WFD's drive for good ecological status, catchment thinking and the inclusion of stakeholders the issue must now be considered and some tough decisions will need to be made. The WFD is therefore a factor that has the potential to encourage the inclusion of Best Available Knowledge; however the way it is interpreted will affect the impact that it has in practice; the acidification issue could, for example, be sidestepped as prohibitively expensive to resolve (Chapter 5).
- **Common pool resource issue:** The issue of forests/fish is not simply an environmental problem; it is a complex issue with economic/social and political ramifications: *the decisions that need to be made are complex.*

10.3.2a(iii) Problems for Forest Practice

- **The economic value of timber:** Forest Enterprise is set up to manage multiple value forestry; it recognises environmental benefits but it retains its responsibility for managing the forest resource. This puts restrictions on the ability of practitioners to act beyond the guidelines: trees will never be felled early (Chapter 5). If this is the case, the wider "forest effect" can only ever be addressed following felling, and the potential for any real change is minimised.

10.3.2b The conception of the "forest effect", as an environmental problem solvable by Science as a factor preventing the inclusion of Best Available Knowledge

The *Forest and Water Guidelines* represent the problem of the "forest effect" as an environmental science problem to which the solution is solely based in an assessment of the environmental risk as indicated by the risk-based approach. In reality the problem is far more complex and pressures are placed on environmental and land managers as a result of the political, social, economic and environmental consequences of any action taken. Decision making needs to take these factors into consideration in addition to Best Available Knowledge and recognise that the solution that is best for the environment may not be the solution that is taken after an evaluation of these wider considerations. This is discussed in more depth below.

10.3.3 Policy Network Linkages

The following section draws on the findings of this thesis to illustrate the importance of relationships within the policy network as factors that both broaden and restrict institutional access to Best Available Knowledge.

10.3.3a Policy Network Impacts on Science

- **Data sharing:** Institutional factors influence the access that individual stakeholders have to different sources of knowledge. The strength of the community level relationship between the GFT and local FC allows forestry practice greater access to better knowledge regarding the "forest effect" represented by the fisheries data. SEPA on the other hand have only recently begun to seek these data. Willingness to share on the side of the data collector and a willingness to include data on the side of the decision maker are key factors affecting the access to Best Available Knowledge (Chapter 5).

10.3.3b Institutional Impacts on Policy Making

- **Responsibility of NGO actors:** Scientists and lay/local knowledge users may have continued to believe in a wider "forest effect" but failed (for whatever reasons) to influence policy. Whatever factors within the network that prevented this taking place are significant as they prevented policy makers having access to Best Available Knowledge.
- **Role of the environmental regulator:** SRPB/SEPA does not see itself as responsible for the Forestry Commission as a fellow government department. Furthermore, it cannot instigate change in forest management practice without FC agreement (Chapter 5). Inter-organisational bonds at the Professional Network level of governance have therefore *minimised* the influence that the environmental regulator has had in terms of influencing the *Forest and Water Guidelines* despite being on the panel. This in turn restricted the impact of any NGO consultation or campaigning that focused on lobbying SRPB/SEPA to address the issues of acidification (Chapter 5). In this way institutional relationships show the potential to

prevent the inclusion of Best Available Knowledge held by both SEPA and the GFT in policy.

- **Consultation and Special Areas of Conservation:** Consultation procedures for the 4th edition of the *Forest and Water Guidelines* did allow NGO bodies the opportunity to convince the Forestry Commission included Special Protection Areas under 300m in their risk-based approach. This means that the Bladnoch is considered for Critical Loads testing. This would be a positive move towards a better inclusion of Best Available Knowledge if the Critical Loads approach was effective.
- **Institutional Independence:** SEPA and the FC have independently determined how to approach the WFD without determining whether their approaches will mesh. SEPA has classified rivers as "at risk" in areas where the *Forest and Water Guidelines* do not apply, yet they recognise the Guidelines as their approach to managing that risk. As forest management will ultimately determine the "forest effect" if the *Forest and Water Guidelines* are not changed to match SEPA's classification this institutional independence will restrict the ability of the Forestry Commission to follow Best Available Knowledge of the "forest effect".

10.3.3c Policy Network Impacts on Forestry Practice

- **The hierarchical power of the guidelines:** The hierarchical mode of governance applied by the *Forest and Water Guidelines* limits the extent to which practitioners can go beyond the guidelines in terms of identifying areas at risk. Forest Managers must follow the guidance of the decision making tools (Critical Loads) embedded in the guidelines, even if ecological data indicates otherwise particularly when regulating private forestry. As a result the *Forest and Water Guidelines* limit the ability of Forest Managers to address the wider "forest effect" recognised by Best Available Knowledge.
- **The role of the environmental regulator:** SRPB/SEPA does not see itself as responsible for the Forestry Commission; they use the Forestry Commission's *Forest and Water Guidelines* to manage the "forest effect". SEPA has been influential over forest practice by assuring that the *Forest and Water Guidelines* are followed but do not act where the guidelines don't apply. As a result any environmental knowledge held by SEPA regarding the "forest effect" is restricted from influencing practice.
- **Inter-stakeholder Trust:** Trust built up between the Forestry Commission and the GFT have lead to the Forestry Commission at a local scale modifying its practice by widening buffer zones in some cases up to c. 100m in areas outside of the *Forest and Water Guidelines* zones. This is a positive move towards addressing the "forest effect" put forward by Best Available Knowledge; however, its impacts in practice will

depend on the extent to which buffer zones are effective in mitigating the "forest effect"; this is currently unclear.

- **NGO Lobbying:** The Cree Bank incident where NGO lobbying by the GFT lead to the local council objecting applying hierarchical/professional network pressures to stop a forest planting is the single most significant factor by which Best Available Knowledge of the "forest effect" was initiated in practice.

10.3.3d Policy Network relationships

Policy Network relationships are therefore an important factor which can both encourage and impede the inclusion of Best Available Knowledge within policy and practice. Community-level links based on trust and sharing of knowledge are ideal for assisting the inclusion of Best Available Knowledge. Strong hierarchical or professional network bonds (Tenbensel, 2005) are, however, not necessarily conducive to knowledge transfer: professional bonds between government institutions were shown to neutralise the potential for the inclusion of Best Available Knowledge in forestry policy. These findings fit well with the findings of other authors who discuss the process of "knowledge deliberation" (Hajer, 2003) and the processes by which stakeholders form coalitions with other actors to influence decision making and demonstrate similar findings with reference to the acid rain debate in the UK (Hajer, 1995), UK water pollution policy change (Jordan and Greenway, 1998) and discussions surrounding the greenhouse effect in Australia (Bulkeley, 2000).

10.4 Discussion and Management Recommendations

10.4.1 Approaching Policy

10.4.1a Why have policy?

In a situation where forest practitioners at a local level are adapting better to local concerns than policy designed for national application the following question is raised: is there a need for policy? If local managers can address the issues at a local scale isn't the Forestry Commission being intelligent in providing them the flexibility to do this? Is "beyond the guidelines" the best approach?

There are two answers to this question. Firstly, a "beyond the guidelines" approach is acceptable, in principle, *if* the advice in the guidelines matches Best Available Knowledge. The problem with the current *Forest and Water Guidelines* is that by forcing forest practitioners to abide by the Critical Loads model, and not encouraging them to take a variety of water quality variables into consideration, they are focusing on a model that does not reflect Best Available Knowledge of the "forest effect". Even if the Critical Loads model accurately identified the "forest effect", a single empirical quantitative measurement cannot be used to determine objectively what is "right" for the river to which many stakeholders have competing claims to use. An approach based on consultation and a suite of measurements (as suggested by the new local SEPA representative in section 7.2.5) would provide a much more legitimate approach to decision making.

A second consideration is the fact that rules are needed; they are important to ensure that there is a baseline on which to build practice so that management practice can be standardised and guided by wider knowledge. This is particularly significant in cases where government and non-government institutions are governed by the same regulations; private forestry is less obliged to go "beyond the guidelines", but the existence of the guidelines provides a good minimum standard. Furthermore the fact that the *Forest and Water Guidelines* are continuously revised is also important as rules need to reflect best available knowledge and this will constantly evolve.

Practitioners should be encouraged to go beyond the guidelines and applauded for the precautionary efforts they have already made. The following sections focuses on the *Forest and Water Guidelines* and suggests modifications drawn from the findings of this thesis for potential modifications to the 5th edition of the Guidelines as well as reflections on the approach taken to the catchment management issues raised by the WFD as a whole.

10.4.1b Being Constructively Constructivist: Social Learning

The aim of this thesis is not to pick apart the decision making of the variety of actors who have been involved in the complex issue of managing the environment in Galloway: I am more than aware of my own partial knowledge of the situation, and recognise that the actors involved will have made considered decisions responding to competing pressures from within and without the organisation in which they are situated. The aim is instead to highlight the factors that can influence the potential of actors involved in decision making to gain access to "Better Available Knowledge", and suggest a Social Learning approach to management as a means to avoid the burden of scientific proof.

As discussed in the first and second chapters, the Social Learning approach argues that the need for scientific proof is removed. Science is always used by someone for some purpose and it is only when social actors accepted it as sufficiently credible that decisions will be based on it. Social Learning argues therefore that well informed consensus is a far better standpoint for decision making than the technocratic approach that we have seen applied to the issue of the "forest effect" within this thesis.

Decisions over a common pool resource are difficult due to subtractability: if forestry is encouraged in sensitive areas the "forest effect" presented here suggests that according to Best Available Knowledge fish are likely to suffer. This will affect the ability of a water course to achieve good ecological status. But do we know that extracting the trees will help? In the upper Cree there has been some recovery of fish after deforestation but is this enough to suggest that the approach will work everywhere? When will it be OK to replant these areas? Is it worth the cost in terms of jobs in forestry to take trees out of catchments? Would it be prohibitively expensive? Or do we side-step the issue and aim for a lower level of environmental status for the purposes of the WFD blaming an international pollutant source or the prohibitive costs?

In considering this it is necessary to reflect on the Water Framework Directive's drive towards "good ecological status" for UK's water courses by 2012. We also know that the Forestry Commission and the Scottish Environmental Protection Agency have responsibilities to achieve this and we know that the precautionary principle is embedded in forestry strategy (FC, 2007) and the WFD itself (EC 2000).

Section 10.4.2 reflects on the findings of this thesis to suggest a re-consideration of the way that the environment is approached in the decision making surrounding the *Forest and Water Guidelines*. This thesis has well demonstrated the dangers of making decisions on the basis of science alone, and that the "*institutionalised rationality of scientists and experts has become a source of problems itself*" (Beck, 1992). By considering consensus the answer to the questions above becomes: what do the stakeholders involved agree is the best approach when presented with the best available science?

This thesis has shown that the questions of which stakeholders to include and where to draw the line is vital in terms of how robust the decisions that are made will be: by restricting the decision making panel to government organisations decisions may have been facilitated: but the decisions made were wrong. For issues of the "forest effect" private forestry and fisheries interests are obvious additional NGO consultees. In moving away from a rigid pseudo-objective Science-based approach it may be worth considering the three sampling factors suggested by Cook and Crang (2007) for rigorous subjectivity: the adequacy, sampling and saturation of viewpoints. The stakeholder group may be big enough when the views represented start to repeat and small enough if the key views in the debate are represented. Reed *et al.* (2008) provide a more considered view of this.

Ultimately the responsibility for managing the environment rests with the environmental regulator: in the case of the "forest effect" in Galloway this is SEPA. The final decision after consultation and inclusion of best available science will rest with them. In considering their decision making they will need to weigh up the factors raised by all parties and decide on the best approach based on their own institutional drives as set out by the WFD. The issue is complex and if forests are found to be more economically valuable than fish then so be it: however, the polluter pays and precautionary principles as well as the drive for good ecological status should mean that this is not a decision that should be reached lightly.

The Forestry Commission as a responsible body will need to work much more closely with SEPA. The *Forest and Water Guidelines* are an excellent institution in principle, but if they are not meeting the needs of the WFD as interpreted by SEPA then they are not sufficient and will need to change. This is not to say that SEPA is right and the FC is wrong: the wider informed consultation around the "forest effect" will ensure that the guidance over catchment management better reflects concerns of *all interested parties* and that management decisions are more equitable and transparent.

10.4.2 *The 5th edition of the* Forest and Water Guidelines

The following sub-topics address key changes to the *Forest and Water Guidelines* suggested by my own interpretation grounded in the analysis of Best Available Knowledge created in the preceding thesis. I appreciate that the suggestions are idealistic and make no attempt to consider any political/social/economic or even wider environmental costs beyond those to water chemistry. This is deliberate; decisions around the environment are complex and will be contested. This thesis is just one further source of knowledge in a continuing learning process and not a definitive answer to the problem. The following section provides suggestions for the 5th Edition of the *Forest and Water Guidelines*.

10.4.2a The Forest and Water Guidelines panel

Widen the panel.

A wider stakeholder group is recommended; the group would aim to target the variety of positions around the issue. It would appear that mere consultation of these outside parties was not sufficient to effectively mould the guidelines towards a better informed knowledge. It is unlikely that the variety of required views will be included by containing solely government institutions; this should be avoided. As mentioned above fisheries and private forest interests would be good starting points, as would an inclusion of academics, local knowledge groups and forest practitioners. A wider panel may make for harder decision making, but can only lead to more informed decisions. The responsibility for the final decision should rest with SEPA not the FC, as the overriding international policy, the WFD, is SEPA's ultimate responsibility.

10.4.2b Identifying areas at risk

The 300m rule should be removed.

The "forest effect" is present below 300m; restricting forest planning to areas over 300m prevents the policy addressing areas at risk. If it were not for the inclusion of Special Areas of Conservation, the Bladnoch, a key international conservation site for Atlantic salmon, would be excluded. The 300m rule, areas of sensitive geology and Critical Loads exceedance are designed to filter to areas at risk from the "forest effect": the WFD makes this something for SEPA to decide. It has characterised rivers as at risk of the "forest effect" and it is these rivers that will need remedial management under the WFD.

Whilst ultimately decisions for the targeting of areas at risk would be best made through consensus with stakeholder parties, in the current situation a good starting point would be to use SEPA's characterisation of areas at risk from the "forest effect" as the rivers in which catchment-based tests (see 10.4.2c) should apply. This is supported by the Best Available Knowledge from this thesis which suggests that these areas match both science and local knowledge as sites at risk. It is however recognised that the FC will have to agree to any changes in management practice: this would ideally happen through consultation within the wider forest panel.

10.4.2c Testing catchments for risk

The Critical Loads model in its current form is not sufficient as a means of identifying the "forest effect".

The Critical Loads approach works well as a means of identifying the areas where geological sensitivity makes areas prone to acid inputs. It does not however highlight the lowland areas where the "forest effect" is identified. It is not therefore reliable in its current form as a means of identifying the wider "forest effect". This will remain the case if an ANC value of 20 is used, and increasing values beyond this is likely to lead to the whole of Galloway being selected, thus minimising the point of using the approach.

In place of the Critical Loads model, decisions would (ideally) be made on the basis of a Social Learning approach based on consensus drawn from Best Available Knowledge of the area based on local knowledge and referring to empirical data drawn from a suite of chemical and ecological samples.

10.4.2d Approach to areas at risk

The current guidelines advocate that if a potential restock fails a Critical Loads test the FC would "*consider objecting to new planting or restocking until pollutant deposition falls below the critical load.*" (FC, 2003b); this would mean that only 30% of a catchment could ever be afforested with conifers if it is identified as at risk. This should be kept in mind as the FC's recognised position of good management for water quality protection. However, under conditions of a potential wider "forest effect", and without the Critical Loads approach the FC may want to reconsider this stance, particularly in light of the potential political/economic/social and environmental ramifications of widespread deforestation and land use change.

The key recommendation regarding this aspect is that, whatever the approach taken, it should be agreed in consideration of these wider implications as well as the impacts on other land uses within the catchment. Will the changes, for example, impact flooding or sediment delivery? Are the jobs related to forestry more important than the fish? These questions need to be asked discussed through wider consultation and answered in a transparent manner.

10.4.2e Encourage a recognition of uncertainty

The Guidelines should be happy to stress the complexity of the issue; it is far more honest and transparent than suggesting that the current scientific methods put down will help minimise acidification when this is unclear. We do not know that deposition reductions will remove the "forest effect"; they may well, but they may not: consensus must be reached as to how to deal with this uncertainty. Ideally, forest managers should be actively encouraged to adapt to local conditions following the precautionary principle as set down in the forest strategy (FC, 2007). Differences from currently accepted science should be identified and explored and not explained away or ignored; the inclusion of lay/local knowledge in a wider *Forest and Water Guidelines* panel will help with this.

10.4.3 Summary: The Forest and Water Guidelines

The fact that the *Forest and Water Guidelines* exist to be critiqued is a very positive sign; and one that the Forestry Commission should be proud of. They are a long way in front of other land uses, particularly agriculture in terms of minimising their impacts on the water environment (Cf. DEFRA, 1998 and 2002). Their technocratic approach to decision making is understandable and a recognised approach seen in many other sectors (Hajer, 1995). It is, however, no longer appropriate: the current 'age of the environment' supported by drives for sustainability from the Rio declaration (UN, 1992), good ecological status from the WFD (EC, 2000), and the application of the precautionary principle and multiple benefit forestry from the Forestry Commission itself (FC, 2007), suggests that the a more inclusive, better informed, less *certain* approach to the *Forest and Water Guidelines* would allow the Forestry Commission to become the leaders in the field of tackling diffuse pollution in the UK.

Chapter 11 : Conclusion

11.1 An interdisciplinary approach

The overarching aim of this study has been to ***investigate the factors that influence the extent to which policy and practice are founded on the best available knowledge of the environment*** using a case study of the "forest effect" on the acidification of freshwaters.

To do this a holistic interdisciplinary approach was taken that contributed to an understanding of the "forest effect" both in terms of the scientific relationships between forestry and water quality and the complexities involved in the environmental management of the "forest effect". This approach was facilitated by following a stakeholder-based methodology. The "forest effect" as a problem was understood by the interpretation of a variety of viewpoints and questions raised by stakeholders were used to direct the spatial and statistical approaches to environmental data. Through an overall evaluation of both stakeholder views and Best Available Science result an interpretation of Best Available Knowledge was achieved.

Best Available Knowledge of the "forest effect" provides a contribution to existing knowledge of freshwater acidification: it has been made apparent that the "forest effect" continues as a threat to freshwater environments despite the decrease in sulphate deposition, that its impacts are more widespread than they are represented in policy and much less well understood. Furthermore, this thesis has contributed additional information to existing monitoring work (Davies *et al.*, 2005) that suggests that forestry may have effects on the long-term recovery of water bodies. The project has also demonstrated the potential of both existing datasets already held by institutional organisations (e.g. SEPA's long-term chemistry data) and remotely sensed imagery as resources to be exploited to contribute more knowledge to catchment management problems. The potential to exploit these known resources remains significant (see 11.2.1 below), and may well be vital in light of the challenges posed by the complexity of the issue at hand.

More significantly, however, the thesis has stressed the relevance of social constructivist critiques for environmental management. Three factors were identified as influencing the extent to which environmental policy integrated Best Available Knowledge i) a failure to recognise that the environment is a complex resource around which many users have contested claims and for which there is no one objective answer ii) a failure to recognise that Science is subjective, fallible and human created and as such inappropriate for use as the sole mediator in environmental decision making and iii) network relationships between organisations were shown to be the key factors that both inhibited and encouraged knowledge exchange between actors; decisions were shown to be based on Better Available Knowledge when they integrated knowledge from other actors, whilst hierarchical and institutional ties showed the ability to minimise the capability of knowledges beyond that represented in policy to be realised in practice.

Approaches to management that recognise these factors exist: Social Learning presents environmental managers with an alternative to the dependence on scientific proof as a means to address the complex environment and its multiple users with their contested arguments over use and access. Ultimately all actors involved in common pool resource, both decision makers and those affected by the decisions must accept that uncertainty and complexity are real; that Science doesn't have all the answers, but that this doesn't stop legitimate decision making being possible. It requires an acceptance on all sides that "*neither the ends nor the means of social interventions can be fully known in advance, and that understanding and consensus on them must be built up through practical experience. Mistakes are unavoidable but with ongoing evaluation results can be improved.*" (Blackmore, 2007) By arguing that decisions should be legitimised by consensus between impacted parties informed by Best Available Knowledge, Social Learning provides a way for environmental management to move forward in a way that, although it will not always be in everyone's best interest, will be legitimate, transparent and socially responsible.

11.2 Further Research Directions

The sections below highlight two major directions in which the research in this thesis could be taken further. The first relies only on the collation of existing data whilst the second puts forward suggestions for a further project to explore both the scientific and social learning considerations identified by this thesis.

11.2.1 Further collation of existing data

11.2.1a Further statistical analysis: ecological investigation

Fisheries and ecology data for the Galloway region are available within GFT and SEPA databases; forest cover data for 5 years were created for this project. Further extending the research in chapters 8 and 9 to include such ecological datasets would contribute to a better understanding of the linkages between forest cover and ecology. This process would be facilitated by the generation of catchments for the ecological sites. Forestry:Ecology relationships would provide useful insights into potential forest management consultations.

A further investigation of local ANC:fisheries data might also be investigated; using existing data will limit this investigation to charge balance ANC (ANC_{CB}). The collection of reliable aluminium, alkalinity and DOC data would allow the correction of Neal *et al.* (1999) to be applied, potentially improving relationships found with any new fisheries data collected.

11.2.1b Further statistical analysis: expand the area

Large resources of untapped water chemistry and ecology data will exist for other acid impacted regions (such as Wales and central Scotland); these data would help to further determine the factors which influence the areas in which the "forest effect" is identified. This will be particularly useful with reference to an identification of a "forest effect" on long-term recovery; combining existing data at a national scale would provide a greater sample size for further statistical analysis of the comparative recovery rates between forest and non-forest sites.

11.2.1c Satellite imagery as a source of forest data

The role of satellite imagery as a means of determining structural data in areas not dominated by monoculture conifer species will need further consideration. The technique has been shown to be robust across sensors and different plantation forests (see 6.5.3a) but further investigation is required to determine the extent to which structural parameters can be extracted for deciduous or mixed forests. In the absence of these data alternative maps of forest extent can be used, but a caveat that the age of the species is unknown would be needed.

11.2.2 Work at the catchment scale

11.2.2a Investigation of the mechanisms

It is clear that the mechanism for the "forest effect" detected in Galloway's low altitude catchments is not clearly understood; there is considerable scope for further work focussing on a catchment or paired catchment scale to improve this understanding. This thesis highlighted the DOC release and sea salt deposition as potential impacts; other "forest effects" raised by local stakeholders, freshwater chemists and ecologists should also be considered for empirical study. The paired Bladnoch and Luce catchments in Galloway would provide ideal case study. Ideally, the work would target multiple high-flow events with as detailed a spatial and temporal analysis as possible to allow the impact of a variety of rainfall events to be studied. Additional parameters such as aluminium (ideally, fractionated), alkalinity and DOC would be comparators as would data from comparative egg-box studies.

11.2.2b Exploring social learning for catchment management

A catchment scale project such as this would provide a perfect opportunity to explore the application of the Social Learning philosophy as an approach to catchment management. A wider stakeholder group would be encouraged to include both private forestry, SNH, local councils and landowners and any other interested parties to focus on the research question: how can the "forest effect" best be understood and managed? This would provide an opportunity to include a consideration of the wider political, economic and social costs and benefits with a wider group of impacted parties to determine to what extent the social learning approach is a feasible alternative to current management practice.

11.2.2c Explore modelling

It is clear that the Critical Loads model in its *Forest and Water Guidelines* form is insufficient to target forest management on areas impacted by the "forest effect"; other models such as FAB(Curtis, 1998) and MAGIC (Wright *et al.*, 1994) could be considered alongside refinements to the Critical Loads approach as additional layers of information within the catchment scale project.

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Appendix A The Critical Loads model in detail

The SSWC model is described in Henriksen and Posch (2001), in the text below an effort has been made to attempt to make it easier to understand!

A critical load is a factor of two things a) the amount of excess base cations in a catchment that are available to buffer acid inputs and b) the safety threshold beyond a point of zero cations needed to maintain an ecological target. The major base cations are sodium, potassium, magnesium and calcium, and they buffer acidic inputs by forming harmless compounds with acid anion inputs thus taking these

Equation A-1 $\quad$ $\text{Critical Load} = BC_{weathering} + BC^{*}_{deposition} - BC_{uptake} - ANC_{limit}$

Equation A-1 expresses this as a factor of three base cation fluxes; Base Cations enter a catchment either as a result of weathering of the bedrock, or through deposition from the atmosphere. Input through sea salt events is seen as a dynamic event and as such the impact of these inputs must be removed from the model; the $BC^{*}_{deposition}$ is marked with an asterisk to indicate that it is corrected for sea salt effects. Base cations can also be removed from the system and BC_{uptake} represents the uptake of base cations into biomass, and subsequent removal by harvesting.

ANC_{limit} is a variable modified by the user to reflect the needs of a target biological organism. In the case of the Forestry Commission's approach an ANC of zero is used for high flow samples as it is seen to represent an equivalent to ANC of 20 at median flows, which is a value at which there is a 90% chance that brown trout populations will be unaffected (Lien *et al.*, 1996). The impacts of this choice of ANClimit is discussed in more detail in section 7.2.2a(ii).

Equation A-2 $\quad$ $BC_{o}^{*} = BC_{weathering} + BC^{*}_{deposition} - BC_{uptake}$

As the calculation of base cation weathering is difficult to attain Henriksen and Posch (2001) advocate an approach that uses only field collected water quality data, and uses the contemporary water quality to back calculate the pre-acidification base cation content, which they refer to as BC_{0}^{*}. BC_{o}^{*} is the overall flux within the catchment, it is calculated using Equation A-2. Substituting BC_{o}^{*} for the three base cation components in Equation A-1 leaves the Critical Loads formula as Equation A-3.

Equation A-3 $\quad$ $\text{Critical Load} = BC_{o}^{*} - ANC_{limit}$

The challenge is then to calculate BC_o^* from a contemporary water sample, which is achieved by following the steps below.

A.1.1a Step 1: Converting to micro equivalents

When a water sample is collected the results are invariably reported in terms of concentrations, often in mgl^{-1}. For the purposes of Critical Loads analyses these need to be converted to micro equivalents, a unit designed for the comparison of ionic strengths. The conversion is performed following the equations in Table A-1; each concentration in mgl^{-1} is divided by its molar mass and multiplying by the ionic charge so that the value represents the relative ionic contribution to the solution.

Table 1 shows the values used for the Relative Molecular Masses (RMM) within the Forestry Commission Critical Loads model; these are standard values, but shown here for transparency. Care must be taken with regards to input data for Sulphur and Nitrogen compounds, as the values are often quoted as the Sulphur in Sulphate (SO_4-S) and Nitrogen in Nitrate (NO_3-N) rather than raw Sulphate (SO_4) and Nitrate. Either can be used, but the conversion to micro equivalents must be appropriate to the form of the input data. This may seem trivial as a point, but it is highly significant in terms of lab methodology (see section X), and can lead to much confusion when interpreting long-term datasets, especially if a change in recording protocol is not reflected in the long-term record.

Table A-1 Converting to Equivalents

Determinant	Ion	Charge	RMM	Equation
X	$X^{Y+/-}$	Y	R	$X(\mu eql^{-1}) = X(mgl^{-1}) * (1000 / R) * Y$
Sodium	Na^+	1	22.99	$Na(\mu eql^{-1}) = Na(mgl^{-1}) * (1000 / 22.99) * 1$
Potassium	K^+	1	39.1	$K(\mu eql^{-1}) = K(mgl^{-1}) * (1000 / 39.1) * 1$
Calcium	Ca^{2+}	2	40.08	$Ca(\mu eql^{-1}) = Ca(mgl^{-1}) * (1000 / 40.08) * 2$
Magnesium	Mg^{2+}	2	24.305	$Mg(\mu eql^{-1}) = Mg(mgl^{-1}) * (1000 / 24.305) * 2$
Sulphate	SO_4^{2-}	2	96.0576	$SO_4(\mu eql^{-1}) = SO_4(mgl^{-1}) * (1000 / 96.0576) * 2$
Chloride	Cl^-	1	35.453	$SO_4(\mu eql^{-1}) = SO_4(mgl^{-1}) * (1000 / 35.453) * 1$
Nitrate (N)*	Nx^-	1	14.0067	$NO3\text{-}N(\mu eql^{-1}) = NO3\text{-}N(mgl^{-1}) * (1000 / 14.0067 * 1$

In this section a worked example is followed through for X individual water chemistry samples to both explain the methodology and provide an indication as to its inner workings.

A.1.1b Step 2: Correction for sea salt

As previously mentioned, sea salt impacts are seen as dynamic events changing the steady state equilibrium. The SSWC model aims to calculate the base cation buffering available from the catchment alone. The deposition of sea salts is known to be a complicating factor, as sea water brings with it small proportions of each of the base cations, as well as a natural deposition of sulphate. The Critical Loads model adjusts for these factors by assuming that all deposited chloride originates from sea salt spray and adjusting all other ions by the relationship between that ion and chloride in sea water (SWR-Cl in Table X), thus as the relationship between sodium and chloride in seawater is 0.86:1 the 86% of the sodium deposited is removed as sea salt derived. As determinants can be corrected in this manner to values below zero these values are replaced by zero. The Forestry Commission deviate from the methodology of Henriksen and Posch (2001) and, in the case of a value being corrected below zero check if any would be identified if the sodium ratio was used instead; if so this value is used; if the value remains below zero it is replaced by zero (Table A-2). All Chloride is removed and all nitrate is assumed to originate from the catchment and is as such not corrected for sea salt.

Table A-2 Sea salt correction

Determinant	Ion	Seawater Ratio		Equation
X	$X^{Y+/-}$	SWR-Cl	SWR-Na	$X^*(\mu eq l^{-1}) = X(\mu eq l^{-1})$ – SWR-Cl * $Cl(\mu eq l^{-1})$
Sodium	Na^+	0.858	1	If $X^*(\mu eq l^{-1})<0$ then:
Potassium	K^+	0.018	0.021	$X^*(\mu eq l^{-1}) = X(\mu eq l^{-1})$ – SWR-Na* $Na(\mu eq l^{-1})$
Calcium	Ca^{2+}	0.037	0.044	If $X^*(\mu eq l^{-1})<0$ then:
Magnesium	Mg^{2+}	0.198	0.227	$X^*(\mu eq l^{-1}) = 0$
Sulphate	SO_4^{2-}	0.103	0.121	
Nitrate (N)*	Nx^-	n/a	n/a	NOT MODIIFED
Chloride	Cl^-	1	n/a	REMOVED

A.1.1c Step 3: Calculate contemporary base cations BC_t^*

Equation A-4 $$BC_t^* = Na^* + K^* + Ca^* + Mg^*$$

Contemporary sea salt corrected base cations are then calculated by taking the sum of the sea salt corrected base cations in the water sample (Equation A-4). The relationship between these and original base cations (BC_o^*) is governed by the same rates of weathering, deposition and uptake that define the original base cations in Equation A-2, with an additional flux in terms of the ion exchange that has happened in the period between the steady state (BC_o^*) and now (BC_t^*); the formula is therefore:

Equation A-5 $$BCt^* = BCo^* + \Delta BC_{weathering} + \Delta BC^*_{deposition} - \Delta BC_{uptake} + BC_{ion\ exchange}$$

The change in rate of $\Delta BC_{weathering,}$ $\Delta BC^*_{deposition}$ and ΔBC_{uptake} are assumed to have remained constant between the two time periods (and therefore equal zero), leaving the relationship between BC_o^* and BC_t^* solely differentiated by the ion-exchange process.

The ion exchange process is governed by changes in non marine inputs of anions, such as anthropogenic sulphate and nitrate and can be related to them using a conversion factor, the "F-Factor" (Henriksen, 1984).

Equation A-6 $BC_{Ion\ exchange} = F \cdot \Delta AN^*$
$= F \cdot (SO_4{}^*{}_t - SO_4{}^*{}_o + NO_{3[t]} - NO_{3[o]})$

The Henriksen (1984) "F-Factor" was estimated by comparison of historical data from Norway, Sweden the USA and Canada and shown to be a value to within the range 0.2-0.4. Brakke *et al.* (1990) modified the Henriksen (1984) relationship to a sinusoidal function based on modern day base cations. This method calculated the F-Factor as a proportion of an overall base cation concentration at which F is equal to 1. This value, "S", has been set to 400 μeql^{-1} or a flux of 400 μeql^{-1} for Norway, a value that is adopted by the UK Critical Loads Advisory Group for nationwide Critical Loads and the Forestry Commission for catchment-based assessments.

Equation A-7 $F = \sin((\pi/2)[BC^*_t]/S$
$F = \sin((\pi/2)[BC^*_t]/400$

To calculate the acid anions flux (ΔAN^* in Equation A-6) requires a knowledge of both current and past sulphate and nitrate values. In the Henriksen and Posch (2001) $NO_{3[o]}$ are "generally set to zero". As contemporary SO_4 ($SO_4{}^*{}_t$) and NO_3 ($NO_{3[t]}$) are known, having been measured in the water sample, it remains to calculate past SO_4. Brakke *et al.* (1989) assume that pre-acidification $SO_4{}^*$ can be calculated in a linear relationship driven by the pre-acidification atmospheric contribution and the contribution from the bedrock geology related to base cation concentrations (Equation A-8). Brakke *et al.* (1989) use values of a=15 and b=0.16 found as the results of a regression based on a sample of 142 lakes in Norway (r=0.38). Other authors have used different values for "a" (varying between 5 and 15) and "b" (varying between 0.05 and 0.17); the Forestry Commission use the values of Brakke *et al.* (1989) (Equation A-8)

Equation A-8 $SO_4{}^*{}_o = a + b \cdot BC_t{}^*$
$= 15 + 0.16 \cdot BC_t{}^*$

Combining Equation A-5 - Equation A-8 produces a final equation for $BC_o{}^*$ calculable only contemporary field measured data of base cations and sulphate (Equation A-9).

Equation A-9 $BC_o{}^* = \mathbf{BC_t{}^*} - (\sin((\pi/2)[\mathbf{BC_t{}^*}]/400) \cdot (\mathbf{SO_4{}^*{}_t} + \mathbf{NO_{3[t]}} - (15 + 0.16 \cdot \mathbf{BC_t{}^*}))$

The critical load can then be calculated by using Equation A-3 and subtracting the selected ANC limit. As the Forestry Commission have selected an ANC of zero BC_o* in Equation A-9 is the critical load; variables in bold are from contemporary water samples.

A.1.1d Critical Load Exceedance

Critical Load Exceedance is the result of the subtraction critical load from the deposited non-marine anion load. For the purposes of determining the anion loading sulphate is assumed to be a mobile anion, and as a result it is assumed that all non-marine sulphate deposited contributes to sulphate leaching (i.e. $S^*_{deposition} = S_{leaching}$). The Forestry Commission use CEH 1995-1997 sulphate deposition maps as their input data for this component.

Upland catchments are considered to be in general nitrate poor, and nitrate is seen to be to a great extent retained within the catchment; as a result nitrogen deposition maps cannot be used to estimate $N_{leaching}$. Instead Henriksen and Posch (2001) advocate using the sum of measured concentrations of nitrate and ammonia in runoff, theorising that it represents the nitrate free to leave the catchment. The Forestry Commission only include the nitrate proportion of this in their version of the Critical Loads model as ammonia plays only a very small role. It is worth repeating that nitrate has not been corrected for sea salt as it is assumed any extra deposition of nitrate will be eagerly absorbed by the catchment.

Equation A-10 $CL_E = S_{deposition} + Nt.Q - BC_o^*.Q$
$= S_{deposition} + N_t \cdot (Rainfall/1.15) - BC_o^* \cdot (Rainfall/1.15)$

The final stage of the process is to convert BC_o* and N_t from μeql^{-1} to fluxes by multiplying them by the discharge from the site. In the absence of accurate discharge date for each catchment sampled the Forestry Commission approach estimates discharge as 85% of catchment rainfall.

Equation A-11 CL_E

$= S_{deposition} + Nt.Q - BC_o^*.Q$

$= S_{deposition} +$

$((Rainfall/1.15) \cdot \mathbf{N_t}) -$

$(\mathbf{BC_t^*} - (\sin((\pi/2) \cdot [\mathbf{BC_t^*}]/400) \cdot (\mathbf{SO_4^*}_t + \mathbf{NO_{3[t]}} - (15+$

$0.16 \cdot \mathbf{BC_t^*}))) \cdot (Rainfall/1.15)$

Appendix B Site Locations

SEPA Sites

NB missing site numbers are from sites outside of the study area not used within the thesis.

ID	X	Y	Name
2	229678	571834	"River Bladnoch @ Waterside (chemistry)"
4	233324	569524	"River Bladnoch @ Glassoch Br (chemistry)"
6	234324	563188	"River Bladnoch @ A75 Rd Br, Shennanton"
9	229793	558712	"Tarf Water Nr Mindork Bridge"
10	239501	555492	"River Bladnoch @ Torhouse Mill"
12	235844	590265	"Water of Minnoch u/s Shalloch Burn conf"
13	236599	589523	"Shalloch Burn u/s Water of Minnoch conf"
14	237287	586481	"Kirriemore Burn @ Kirriereoch Loch"
16	237093	578573	"Water of Minnoch @ Stroan Bridge (chemistry)"
17	237880	578186	"Water of Trool @ Footbridge (chemistry)"
18	234913	576414	"River Cree @ Bargrennan (chemistry)"
19	236225	574845	"Water of Minnoch @ Minnoch Bridge (chemistry)"
21	241069	566508	"Penkiln Burn @ Newton Stewart (chemistry)"
23	241265	565341	"River Cree @ Newton Stewart Gauging Station (chemistry)"
26	256892	592923	"Water of Deugh @ A713 Liggat Br, Carsphairn"
27	261938	590235	"Water of Ken @ High Bridge of Ken (chemistry)"
28	259850	588045	"Polmaddy Burn @ A713 Road Bridge (chemistry)"
30	260321	584364	"Polharrow Burn @ Polharrow Bridge"
32	260292	581079	"Coom/Garroch Burn @ Glenlee"
34	247743	579600	"Loch Dee Outflow"
35	263930	579310	"Garple Burn @ Garple Bridge"
36	248074	578956	"Green Burn u/s Forestry Track"
37	245075	578736	"Dargall Lane d/s Southern Upland Way Track"
38	264034	578360	"Water of Ken @ Ken Bridge"
40	246835	577897	"White Laggan Burn No2, d/s of Black Laggon, S of Loch Dee"
41	246933	577712	"Black Laggan Burn u/s Loch Dee"
42	246833	577705	"White Laggan Burn No3, u/s of Black Laggon, S of Loch Dee"
43	254760	575052	"River Dee @ Clatteringshaws Outfall"
46	266329	570071	"Black Water of Dee at A762 road bridge Mossdale"
47	264708	570013	"Black Water of Dee @ Stroan Viaduct"
49	273345	564173	"River Dee @ Glenlochar Gauging Station"
50	273400	560000	"River Dee @ Bridge of Dee"

51	272939	558585	"Auchlane Burn @ Rivington Lodge"
53	258143	561340	"Little Water of Fleet @ Drumshangan Br"
54	258072	561084	"Big Water of Fleet @ Green Wood"
57	259848	556302	"Water of Fleet at Fleet Bridge Gatehouse (Tidal)"
58	217277	571045	"Cross Water of Luce @ Dirniemow (chemistry)"
59	213650	569770	"Main Water of Luce above Penwhirn Burn"
60	213478	569602	"Penwhirn Burn @ Dalhabboch Bridge (chemistry)"
62	212800	569500	"Penwhirn New WTW, Abs from Penwhirn Reservoir @ Dam"
63	217314	564812	"Main Water of Luce @ New Luce"
64	217378	564612	"Cross Water of Luce @ New Luce"
65	218007	559926	"Water of Luce @ Airyhemming Gauging Station"
66	219160	557340	"Water of Luce @ Railway Viaduct, Glenluce"
67	246002	566299	"Palnure Burn @ Craignine Bridge (chemistry)"
68	256606	555449	"Skyreburn at Skyeburn Mill"

University of Durham Sites

ID	X	Y	Name
1	228200	575600	"Pulgany Burn"
2	228600	573700	"Drumshalloch Loch Outlet"
3	228600	573300	"River Bladnoch"
4	227704	573295	"TRIBUTARY POLBAE AT DARLOSKINE"
5	227991	572910	"Polbae Burn @ Darloskine Br"
6	231420	571355	"Beoch Burn @ Beoch Bridge, Knowe"
7	227600	571100	"Dargoal Burn"
8	232783.3	570268.4	"BURN ORIGINATING NEAR BEOCH ABOVE ROAD"
9	233400	569500	"Glassoch Burn"
10	222700	569400	"Tarf Water"
11	222800	569300	"Purgatory Burn"
12	229135	567757	"PULTAYAN BURN"
14	228300	567400	"Black Burn"
15	224400	567400	"Unnamed Burn"
16	229566	567220	"BLACK BURN DRUMABRENNAN"
17	225372	567216	"AIRIES BURN (UPPER)"
18	228506	566494	"BLACK BURN"
19	222442.3	565201.5	"DRUMPAIL BURN"
20	225507	564802.4	"Tarf Water @ Tarf Bridge"
21	229241	559254.2	"LANNYGORE BURN"
22	234466.3	557773.3	"CLUGSTON BURN (UPPER)"
23	235835	591494	"ELDRICK HILL"
24	235772	590273	"LAGLANNY BURN"

25	235984.2	590038.7	"WATER OF MINNCOH SHALLOCH TRACK"
26	237209	589638	"SHALLOCH BURN"
27	237205.4	589583.5	"KNOCKLACH BURN"
28	235921.7	588101.7	"WATER OF MINNOCH TARFESSOCK"
29	236529.9	587697.9	"PILLOW BURN"
30	234499	586924.3	"CAIRNFORE BURN"
31	235869.2	586661.8	"WATER OF MINNOCH KIRRIEROCH BRIDGE"
32	233448.3	586147.8	"CREE OUTFLOW LOCH MOAN"
33	236301.6	585319.4	"BLACK BURN"
34	228728.1	584450.8	"CLAUCHRIE BURN (MLURI STATION)"
35	236255.3	583230.7	"BUTLER BURN"
36	237034	583070	"WATER OF MINNOCH PALGOWAN"
37	237098	582773	"KNOCKCRAVIE"
38	231440	582295	"LANIEWEE BURN"
39	233086	580905	"CREEBANK BURN TRIBUTARY"
40	233684	580709	"CREEBANK BURN TRIBUTARY"
41	230256	580525	"River Cree @ Arnimean"
42	243542	579723	"LOCHS OF GLENHEAD OUTFLOW BURN"
43	243739	579453	"TROSTAN BURN"
44	232425	579282	"CREEBANK BURN"
45	232455.8	578969.6	"CREE CAIRNDERRY (Site 1)"
46	240179.8	578854.8	"CALDON'S BURN"
47	237122.5	578598.6	"PULNAGASHEL BURN"
48	239699.6	578435.3	"JENNY'S BURN"
49	232203	577092	"CREE DALNAW"
50	237900	575068	"UPPER PULNISKIE"
51	236516	574453.4	"PULNISKIE BURN"
52	243455.7	569101.4	"GLENSHALLOCH BURN"
53	257800	605100	"Bitch Burn"
54	259600	604700	"Water of Deugh"
55	259800	604300	"Fingland Burn"
56	257400	603800	"Polwhat Burn"
57	256700	603600	"Strathwiggan Burn"
58	255800	601300	"SHALLOCH BURN"
59	265600	599100	"SPOUT BURN"
60	257700	599000	"Poultribuie Burn"
61	256600	598200	"Laggeran Burn"
62	255600	597800	"Bow Burn"
63	265800	597700	"CORLAE BURN"
64	256500	596300	"Polsue Burn"
65	256200	595100	"Benloch Burn"
66	255702	594595	"Water of Deugh @ Greenwell Bridge"

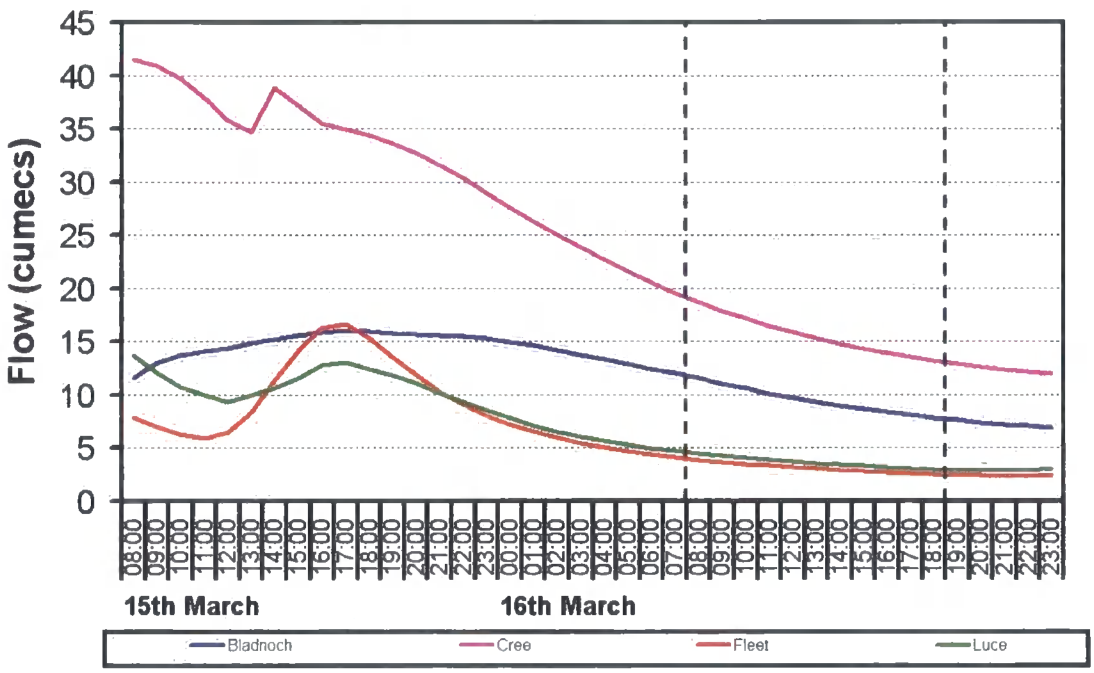
67	261600	588400	"BLACK WATER"
68	259000	584300	"CRUMMY BURN"
69	268100	582800	"CORRIEDOO BURN"
70	256000	582500	"BLACK BURN"
71	262400	576200	"PULTARSON BURN"
72	257300	574700	"BURN AT LAGGAN O'DEE"
73	255900	574300	"GREEN BURN"
74	254400	574200	"PULLAUGH BURN"
75	266100	573900	"Shirmers Burn @ A713 Bridge"
76	259300	573700	"LOWRING BURN"
77	260300	573400	"TANNOCH BURN"
78	257700	573300	"WHITE BURN"
79	257800	573300	"NICK BURN"
80	261400	572950	"MID BURN"
81	263100	571300	"ACRE BURN"
82	261200	571000	"GLENGAINOCH BURN"
83	258000	570500	"UPPER GLENGAINOCH BURN"
84	259300	570300	"GLENGAINOCH BURN"
85	253931	568553	"LOCH GRANNOCH LODGE BURN"
86	266200	567800	"NETHER CRAE UNNAMED BURN"
87	266800	567100	"NAMELESS BURN FLOWING INTO NAMELESS LOCH"
88	267000	565500	"KENICK BURN"
89	257840.4	569197.8	"LITTLE W. OF FLEET WELLEES RIG"
90	258737.2	567193.8	"LITTLE WATER OF FLEET"
91	255308	566954	"CRAIGLOWRIE BURN"
92	254733	566469	"LOWER CARROUCH BURN"
93	254807.7	566440.9	"MID BURN"
94	255873	565825.4	"BENMEAL BURN"
95	254596.8	565236.1	"CARDOON BURN TRIBUTARY"
96	255829.4	565184.1	"BIG W. OF FLEET MEIKLE CULLENDOCH"
97	259554.3	565098.1	"BURNFOOT BURN"
98	264950	559900	"GLENGAP BURN TRIBUTARY"
99	265200	559400	"GLENGAP BURN"
100	217297	578093	"ARECLEDOCH STREAM"
101	217000.1	577407.3	"MULL BURN PEAT HILL"
102	212796.4	572694.1	"LAGANABEASTIE BURN"
103	213332.3	571048.4	"MAIN W. OF LUCE DALNIGAP"
104	214429.8	568603.3	"MAIN W. OF LUCE WOODEN BRIDGE"
105	218456.2	568052.3	"CROSS W. OF LUCE QUARTER FARM"
106	216697.6	565795.9	"MAIN W. OF LUCE LITTLE LARG"
107	219403	565224.5	"CROSS W. OF LUCE ABOVE BARNSHAGEN"
108	274200	581300	"MONYBUIE BURN TRIBUTARY"

109	270300	584600	"LOCH HOWIE BURN"
110	251814	572235	"PALFERN BURN"
111	250001	571865	"DUNKITTERICK BURN NORTH"
112	249905	571800	"DUNKITTERICK BURN SOUTH"
113	247518	569180	"LOURAN BURN"
114	248619	568728	"UPPER LOURAN BURN"
115	255164.8	558138.8	"SKYRE BURN BELOW JUNCTION AT ARKLAND B."
116	255800	601600	"Unnamed Burn"
117	254900	600600	"Brownhill Burn"

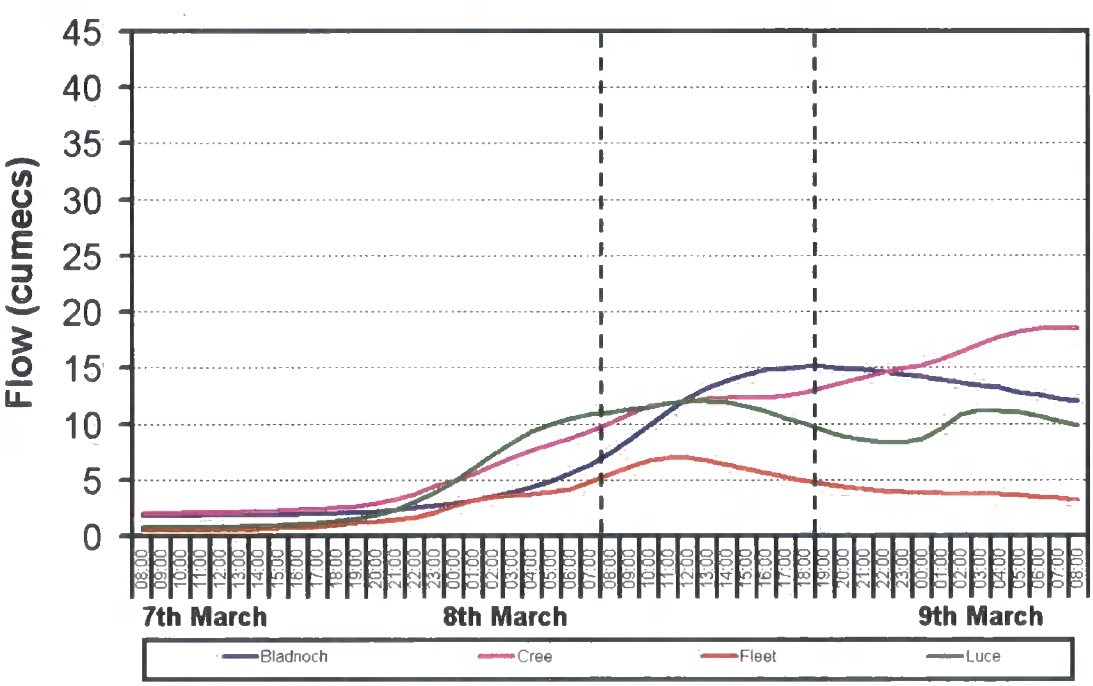
Appendix C Hydrology for High Flow Data

Low flow averages (taken from 06/03/2006): Bladnoch – 1.83 cumecs; Cree – 2.07 cumecs; Fleet – 0.51 cumecs; Luce – 0.78 cumecs

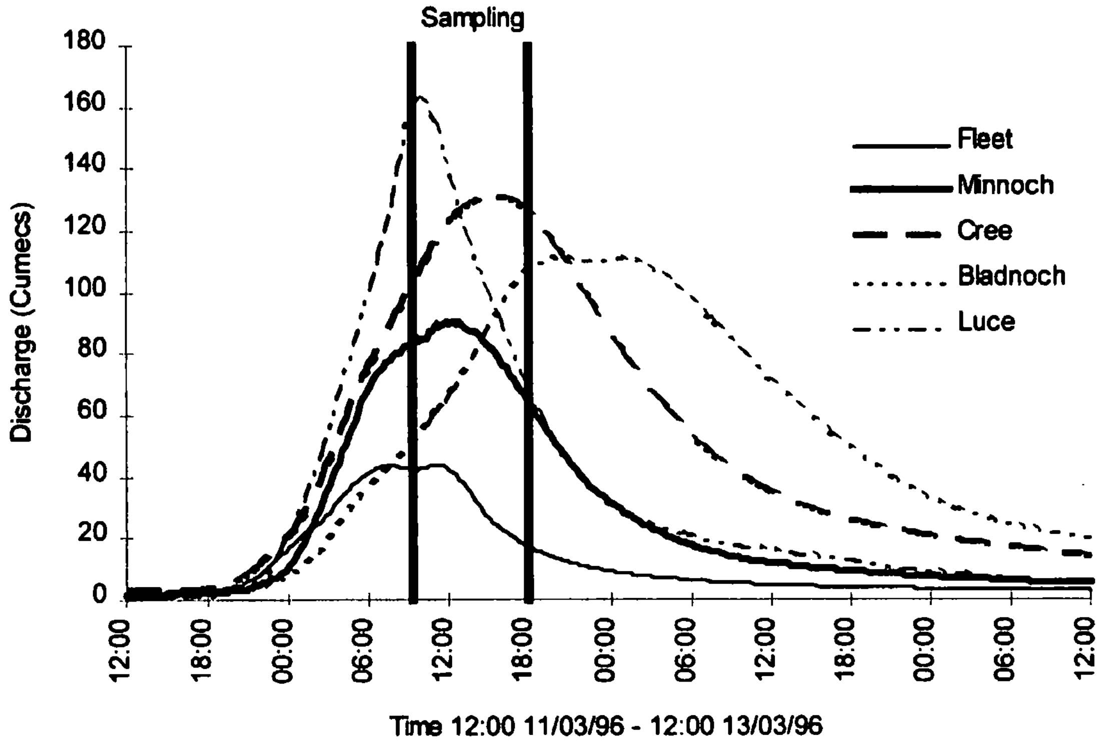
Storm Event : 16th March 2005 (Data from SEPA long-term flowguages)



Storm Event : 8th March 2006 (Data from SEPA long-term flowguages)



Storm Event: 12th March 1996 (from Puhr *et al.*, 2000)



Sampling
180
160
140
120
100
80
60
40
20
0
Discharge (Cumecs)
Fleet
Minnoch
Cree
Bladnoch
Luce
12:00
18:00
00:00
06:00
12:00
18:00
00:00
06:00
12:00
18:00
00:00
06:00
12:00
Time 12:00 11/03/96 - 12:00 13/03/96

Appendix D Dunford & Donoghue (2007)

FORESTRY, REMOTE SENSING AND CATCHMENT MANAGEMENT: OPTICAL IMAGERY FOR LONG-TERM TREE HEIGHT MAPPING.

PAPER PRESENTED AT RSPSoc 2007; Newcastle

R.W.Dunford*, D.N.M. Donoghue.

Department of Geography, Durham University, Science Laboratories, South Road, Durham, DH13LE.
R.W.Dunford@durham.ac.uk

KEY WORDS: Forest Parameter Estimation, Catchment Management, Optical Imagery, Landsat, SPOT, LiDAR.

ABSTRACT:

With the introduction of the Water Framework Directive in 2000 the demand for high quality information for catchment management has never been as pressing. In areas suffering from acidification, where the potential for the filtering of atmospheric pollutants by forestry increases with tree height it is vital to know not only the proportion of forestry within a given catchment but also an indication of its scavenging potential. Existing science has used optical satellite imagery to model tree height from forest establishment to canopy closure. This paper develops this work to produce a time series of forest height change from 1989 – 2005 using a series of five radiometrically calibrated optical images and tree height data from a single year (2003). The success of the methodology is validated against field measured data from two other years 1995, 2001 showing a mean difference from measured tree height of 1.43m and a standard deviation of 1.04. This compares well with both the error found between LiDAR measured field height and field measurements, and indeed the inherent measurement error of field measurements themselves. The success of this technique provides i) catchment managers a regional scale tool to relate long-term changes in the forest filtering potential to its chemical and biological factors ii) the capability to monitor forest establishment in years where no ground truth data are available by using paired ground truth data and imagery from another year and a radiometrically corrected optical image from the year of interest.

1. INTRODUCTION

1.1 Forestry and catchment management

Acidification of freshwaters resulting from the deposition of airborne atmospheric pollutants has been a significant problem for catchment managers, environmentalists and fisheries over the past twenty years. Historically the potential exacerbatory role of forestry in this has been the focus of much academic interest and debate (Rosenqvist, 1978; Wright *et al.*, 1980; Battarbee, 1984; Welsh Water, 1987; Ormerod *et al.*, 1989; Nisbet *et al.*, 1995; Nisbet, 2001). In the UK the introduction of the Forestry Commission's "Forest and Water Guidelines" (Forestry Commission, 1988, 1991, 1993, 2003b) showed a recognition by the forest industry of the potential impacts of forestry on the water environment. In the third and fourth editions of the guidelines the impacts of the forest are explained as:-

"Forest canopies can significantly increase the capture of some of these pollutants in the atmosphere. This increased capture, often termed scavenging, is a function of the stand structure which creates turbulent air mixing. The effect therefore becomes more important as trees grow and the height of the stand increases" Forestry Commission, 2003 (p15).

In 2000 the "Water Framework Directive" (WFD, 2000/60/EC) was introduced at an EU level with the aim to restore European water bodies to "good ecological status". This put a focus on tackling diffuse source pollution and, as a result, policy implementers and forest managers alike gained a pressing need for timely, regional scale information on the structure of the forests within the catchments they manage. As scavenging is seen to increase with tree growth towards a developed canopy structure, the information required by forest managers is not only in terms of the proportion of forestry within a catchment, but the canopy closure status of that proportion.

1.2 The Study Area

The impacts of acidification on the water quality and ecology of Galloway Forest District in Southwest Scotland (Figure 1) has been studied for many years (Wright *et al.*, 1980; Battarbee *et al.*, 1985; Battarbee *et al.*, 1989; Allott and Harriman, 1992; Puhr, 1997).

Figure 1. Study area

Although there is some evidence that the trend in airborne pollution at a European scale has decreased over recent years with sulphate emissions as 70% lower than their 1980 levels (NEGTAP, 2001), approximately 275km of river in of Galloway forest district has been classified by the Scottish Environmental Protection Agency (SEPA) as at risk of failing the water framework directive as a result of acidification due to forestry (Figure 2).

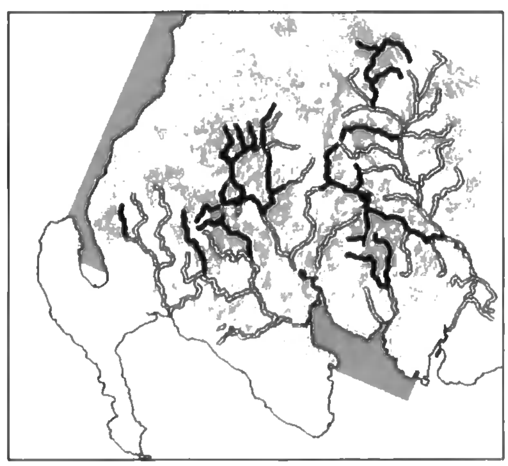


Figure 2. Rivers classified by SEPA as definitely/probably at risk of failing the water framework directives environmental quality targets as a result of acidification exacerbated by forestry (in black).

Helliwell *et al.*, 2001 indicate that whilst there is evidence of a recovery in terms of water chemistry within the region, forestry is continuing to hamper ecological recovery. Long-term records of chemistry and ecology exist at a regional scale. However without a long-term record of forest cover and more specifically canopy closure available at the same scale it is extremely difficult for catchment managers to make informed decisions about the environment.

1.3 Optical Remote Sensing for the monitoring of forest establishment

Li and Strahler, 1985 modelled the relationship between reflectance in optical imagery and forest height resulting from the changing proportions of lit and shaded canopy and ground. These proportions change as a forest establishes and shades out ground vegetation resulting in a gradual change in reflectance from more SWIR-reflective ground vegetation to closed canopy forestry. Once canopy closure is attained, forest height no longer influences the proportion of ground vegetation visible to the sensor and the limit of the predictive power is reached. For the managed forests of Galloway this limit has been shown to be at around 13m in height (Puhr and Donoghue, 2000).

There is significant published work that has applied this model. Puhr and Donoghue (2000) derived strongly significant relationships between plots of forest from Galloway and Landsat 5 reflectance, particularly in the short wave infrared (SWIR, R^2 = 0.94 P<0.01). Further work extended the methodology showing that the relationship was robust across different optical sensors (SPOT, Donoghue *et al.*, 2004, IKONOS Watt and Donoghue, 2007) and forests (Galloway Forest, Puhr and Donoghue, 2000, Donoghue *et al.*, 2004; Kielder Forest, Watt and Donoghue 2006) again producing highly significant results (R^2 0.818, P<0.01, RMSE 0.984m). Once determined such regression equations can be inverted to produce regional maps of tree height based on the image (Puhr and Donoghue, 2000; Watt and Donoghue 2006).

1.4. Aims and Objectives

This paper builds on established knowledge of the relationship between forest growth and SWIR reflectance and applies the relationship found between one image:fieldwork pairing to a timeseries of radiometrically corrected images. Its aim is to be able to produce forest establishment maps from images for which field data are not, and can never be, available and b) for these maps to provide value added information on canopy closure that can be used by catchment managers to inform decision making.

A note on terminology: from this point on the term SWIR is used to describe the range of electromagnetic radiation between 1.53-1.75μm equivalent to SPOT 5 band 4 or Landsat 7 band 5.

2. METHODOLOGY

2.1 Methodology Overview

The following is a summary of the approach used in this paper:-

i) Collection of datasets.
ii) Radiometric cross-calibration of optical images.
iii) Determination of relationship between tree height and SWIR reflectance.
iv) Validation of height maps with independent datasets.

2.2 Datasets

Three Landsat (11/7/1989, 21/6/1995 and 1/5/2001) and two SPOT (17/4/2003 and 15/7/05) images were used making a time series of five images 1989 -2005. Measured forest height information was available for 97 field plots from 1995 (from Puhr, 1997), 58 field plots from 2001 (from Donoghue *et al.* 2004) and 113 ground plots from 2003 (collected as part of the ForestSAFE project, ForestSAFE, 2003). A 10m grid of LiDAR tree height (flown on 28/07/2003) was also available.

2.3 Radiometric Calibration

For comparisons between pixel values to be possible for a time series of imagery data it is important that the datasets are radiometrically calibrated to one another to take into account differences in atmospheric conditions and illumination specific to the date they were acquired (Hall *et al.*, 1991). Whilst atmospheric correction models are available (Kaufman and Sendra, 1988; Kim and Elman, 1990) these require additional empirical data about the atmospheric condition at the time of data capture rarely available to those keen to use the imagery. As a result a linear regression approach is used that assumes scattering and atmospheric adsorption produce a linear shift between images (Chavez, 1988; Du *et al.*, 2002). Spectrally invariant features can then be identified in the images and the relationship between their reflectance used to calibrate the images to one another. 13 dark-target water bodies, and 8 bright targets including exposed quarry rocks and airstrips were used to correct the images to the radiometry of the same reference image (a Landsat scene from 2003).

The method produced R^2 values ≥ 0.96 with $p<0.001$ for each SWIR band (Table 2). This encourages confidence in the approach in terms of little error introduced from scatter around the regression line. The residuals are distributed heteroscadastically with greater scatter about the line at higher DN values and significantly less scatter for the darker targets. This is seen as particularly encouraging, as it is the lower DN range (between 60-20 for the images used for this paper) that is key for the estimation of forest growth and where the model is at most risk from errors resulting from radiometric correction.

Image	R^2	RMSE
Landsat 1989	0.96	7.46 DN
Landsat 1995	0.97	7.28 DN
Landsat 2001	0.97	6.98 DN
SPOT 2003	0.96	8.28 DN
SPOT 2005	0.99	2.70 DN

Table 2. Results of radiometric correction of SWIR band.

2.4 Determination of relationship between tree height and SWIR reflectance

2003 was selected as the base year for the generation of the relationship between field data and SWIR reflectance. A 15m buffer was applied to a 10m grid of LiDAR tree height (first pulse-last pulse) to extract tree height measurements. The relationship between the 113 ground measured tree heights and the gridded LiDAR values are shown in Figure 3.

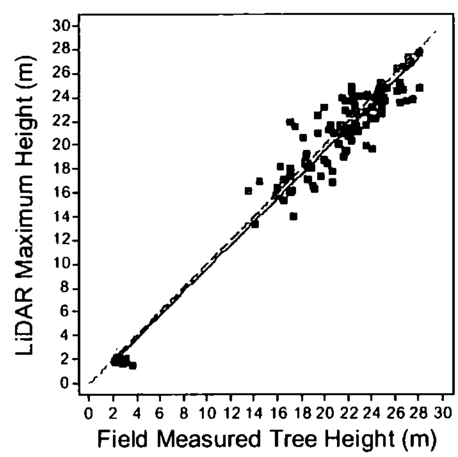


Figure 3. The difference between LiDAR and ground truth over 113 sites.

The difference between the two measures of tree height was calculated to have a mean of 1.44m and a standard deviation of 1.04.This would no doubt be closer if non gridded LiDAR data were used, but was seen to be sufficiently precise for the purposes of the modelling exercise in light of the additional advantages provided by the use of a LiDAR Image. Firstly, whilst LiDAR height is known to consistently underpredict tree height (Holmgren *et al.*, 2003) this is an error of precision rather than accuracy, a bias that can be taken into consideration. Conversely field measurement is prone to errors of accuracy, varying unpredictably due to the difficulty of viewing canopy crowns and other errors resulting from measurement by a variety of operators and techniques. Secondly, whereas field data are often targeted at a particular age class/classes it was possible to sample LiDAR data across the breadth of classes available in the image extent. This was particularly relevant for this paper as the 2003 ground survey dataset was targeted at the two extremes (0-3m, and >14m) with no coverage covering forest establishment between 3-13m. Finally, the LiDAR image facilitates a far more intensive sampling regime without significant amounts of expensive field work. This enabled tree heights for 360 locations to be extracted as the tree height dataset, covering a spread of tree height classes.

The same 360 locations were extracted from the 2003 SPOT image using a buffer of 15m. Regression analysis was then applied to the SWIR and LiDAR to produce a model relating reflectance to tree height.

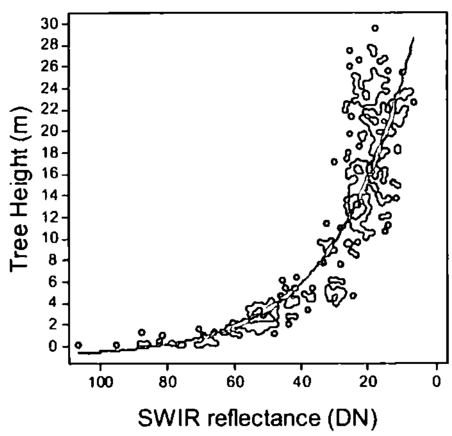


Figure 4. Scatter of SPOT SWIR reflectance from 2003 with LiDAR height (also 2003) for 360 plots. Grey Line is fitted logarithmic regression Tree Height = 10^(1.60– 0.02* SWIR). R^2 = 0.88, RMSE 1.53m

Figure 4 displays the relationship between the data points, and in grey a fitted logarithmic regression line in the form of TreeHeight = 10^(a+b*SWIR). To avoid issues of Log(0) 1 is added prior to calculation, and subtracted from the estimated height at the end. The regression produced has an R^2 of 0.88, an RMSE of 1.53m and a P<0.001. Any predictions resulting in a tree height below 0 were replaced by 0.

2.5 Validation of Tree Height Maps with independent datasets.

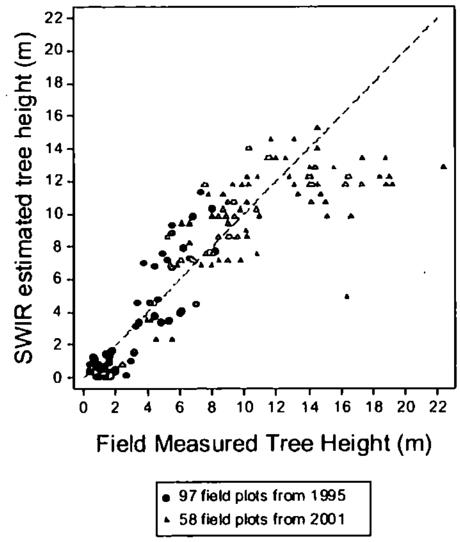


Figure 5 SWIR estimated tree height vs. 155 independent measured tree height plots.

Ground truth data from 1995 and 2001 were used to validate the SWIR based estimations of tree height (Figure 5). Whilst predictive power is lost after 13m as anticipated in the established literature trees below 13m scattered closely around the X=Y line.

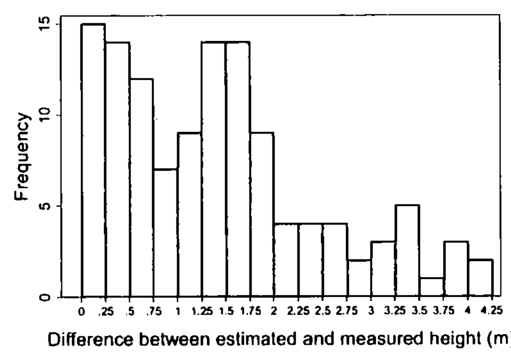


Figure 6 Scatter between estimated and measured tree height.

Figure 6 illustrates the distribution of the residuals around the X=Y line. The mean difference from the measured height is 1.43m with a standard deviation of 1.09; the 75th percentile is at 1.92m.This is of a similar order to the relationship found between LiDAR and field measured height in Figure 3 (mean difference 1.44m, standard deviation 1.04). Furthermore regression analysis indicates a statistically significant positive relationship (P<0.000, R^2 0.86, RMSE 1.62m) reinforcing confidence that the trend shown in the data does not occur by chance.

3. DISCUSSION

The validation of this methodology with independent data from two separate years encourages significant confidence in the technique. This paper therefore indicates that tree heights between 0-13m can be successfully estimated with an average error of 1.43m for any image radiometrically calibrated to a single image: ground truth pairing.

Any discussions over the scale of this error must consider the alternative sources of such information. Ground truth data, if available, is prone to its own measurement errors varying depending on method used and between operators. There have been few studies looking into the size of these errors (Barron, 2001), however Woodget (2007) suggests that even with Vertex III transponder, accurate to 0.1m of itself, (Haglof, 2007) comparison of tree height measurements with felled tree height show an mean scatter of 1.08m with a standard deviation of 1.23.

Furthermore, even if such ground truth data were available it is unlikely that they would be at the regional scale required performing catchment analyses. The undertaking required would be disproportionately expensive and time consuming. It is at this regional scale that the benefits of this methodology are most apparent. In addition to this are the advantages in terms of temporal scale allowing catchment managers access to forest information from years where ground truth data has never been available, within the limits of available cloud free imagery. These data can then be combined with long-term information on water quality and environmental health to inform decision making over the impacts of forestry on water quality.

4. CONCLUSIONS

The work presented in this paper covers a gap in the published literature by putting forward a robust methodology based on established science for the generation of timely forestry data for catchment management. The technique is effective at a regional scale, and across the time period of available optical imagery. With optical datasets such as Landsat and SPOT now considerably reduced in price, and with the current policy climate increasingly driving for better regional scale catchment information this paper encourages organisations with a catchment management responsibility to consider the approach as a cost-effective technique for long-term monitoring and decision support.

ACKNOWLEDGEMENTS

This work is funded under an ESRC/NERC PhD Studentship, and would not have been possible were it not building on the existing work of Drs K. McManus, N. Galiatstatos, P. Watt and C. Puhr. The EU LIFE project ForestSAFE also needs special recognition as, without it, such an impressive collection of field and remote sensing datasets for Galloway would never have been collected.

Appendix E Water Chemistry Data Processing

Table G-1 Water chemistry processing methodology

Field Survey →	Long-term Monitoring	Loch Dee Project	1996 Field Survey	2005 Field Survey	2006 Field Survey
Laboratory	SEPA (D/EK)		SEPA (D)	UoD	UoD
Survey Name	SEPA_LT		Puhr_1996	UoD_2005	UoD_2006
Data Format	68 Spreadsheets (.xls)		1 .xls	1 .xls	1 .xls

Individual Spreadsheets	• 71 Excel Spreadsheets • Filter for key variables and order (VBA Macro):- pH, SO_4, $NO_3(N)$, Cl, Na, K, Ca, Mg, Alkalinity and DOC • Additional Information:- Site name, easting, northing, sampling date. • Combine into one sheet.
	EXCEL DATABASE
Pre-Stata processing	• Give Unique ID by site Numbers1-117: Puhr & Durham Sites Numbers 201-268: SEPA_LT Sites • SEPA_LT ID overrules for the 3 sites that exist in both networks • Export site locations to GIS for pour points • Move data to statistical software
	→ GIS
	STATA DATABASE
Data management	• Convert data from milligrams/litre → micro-equivalents/litre • Check for redundant/duplicate data • Ensure 1 record/day/site (replace with mean) • Remove SEPA_LT alkalinity data • Remove SEPA_LT SO_4 data outside the period 1983-1998
Data Screening	• Na:Cl checks • Compare with AWMN data • Ion balance checks • Outlier Removal
Calculate Derived variables	• xSO_4 • ANC_{CB} • ANC_{CA} • 4 x CLoad Scenarios
Generating Site Summary variables	• Puhr and Durham data have only one record • Summary Statistics for SEPA_LT data Annual (if ≥ 4 records) Median, Mean, Maximum and Minimum
Water Chemistry Database	• Database ready to join with Fish / Catchment Data

E.1 Conversion to micro equivalents (μeql^{-1})

As a first step to data analysis water chemistry variables were converted to micro-equivalents litre^{-1} by dividing them by their ionic mass[23]. The values used from conversion are those used by the Forestry Commission in their Critical Loads calculations. Note: sulphate is referred to as total sulphate whilst nitrate is reported as the nitrogen component of nitrate.

- Na (μeql^{-1}) = Na (mgl^{-1}) *1000/22.99
- K (μeql^{-1}) = K (mgl^{-1}) *1000 / 39.1

[23] Different from the molar mass in that it takes ionic charge into consideration.

- Ca (μeql^{-1}) = Ca (mgl^{-1}) * 1000 / (40.08/2)
- Mg(μeql^{-1}) = Mg (mgl^{-1}) * 1000 / (24.305/2)
- SO4 (μeql^{-1}) = SO4 (mgl^{-1}) * 1000 / (96.0576/2)
- Cl (μeql^{-1}) = Cl (mgl^{-1}) * 1000 / 35.453
- NO3(N) (μeql^{-1}) = NO3(N) (mgl^{-1}) * 1000 / 14.0067
- Alk ($CaCO_3$) (μeql^{-1}) = Alk ($CaCO_3$) (mgl^{-1}) *1000 / (100.0932 / 2)

E.2 Dealing with detection limits

Limits of detection are imposed by laboratories when the quantities of anylant are found to be below a limit at which the determining methodology can confidently differentiate detection from background readings. Under these conditions all that is known with any robustness is that the "true measurement" is less than a given censoring value. As a result any values reported back are either reported as "Below the Detectable Limit" (BDL) or as a "less-than" figure, such as "<0.1 mg/l". These data whilst representing the best available knowledge are not useable in any further analysis such as linear or multiple regression. The issue is further complicated for long-term studies where more than one laboratory/ methodology has been used to measure the anylant, leading to more than one detection limit applied.

As a result a variety of methodologies (Table G-2) have been put forward to deal with the issue as demonstrated in Baccarelli et al (2005).

Table G-2 Dealing with detection limits (from Baccarelli et al. 2005)

Procedure	Method	Validity: Mean	Validity: Standard Deviation	Uncertainty due to non-detectable values
Deletion	Non-detects discarded	Overestimated	Underestimated	Unaccounted for
Simple Substitution				
Zero	"BDL" replaced with 0	Underestimated		Unaccounted for, substituted value treated as true.
DL/2	"BDL" replaced with half detection limit	Bias small if:- • Frequency of non-detects is low (<15%, USEPA, 2000) • Highly skewed data (assumed uniform distribution)		Unaccounted for, substituted value treated as true.
DL/√2	"BDL" → replaced by DL/✓2	Bias small if:- • Frequency of non-detects is low (<15%, USEPA, 2000) • NOT Highly skewed data (assumed triangular distribution)		Unaccounted for, substituted value treated as true.
DL	"BDL" replaced by the DL	Overestimated	Underestimated	Unaccounted for, substituted value treated as true.
Distributional	Mean and SD estimated using assumptions on underlying data distribution	Bias small if:- • Actual data do not depart from the assumed distribution • <50-60% non-detects		Unaccounted for
Distribution-based imputation	Imputes a value drawn from assumed underlying	Unbiased even if:- • Data show mild/moderate		Accounted for by multiple imputation

distribution	departure from the assumed distribution • 60-70% non-detects

The most robust approach, recommended by both Bacarrelli et al (2005) and Helsel (2006) is to impute values for BDL values. However other organisations such as the United States Environmental Protection Agency (USEPA) advocate a simple substitution approach for distributions where less than 15% of the data are BDL. As for my data only Nitrate had a greater proportion of below BDL values (17.22%) see Table G-3 the methodology of Hornung and Reed (1990) was followed with values for all variables below the detectable limit were replaced by BDL/2.

Table G-3 Distribution of BDL values by Survey

	SEPA Long-term	Puhr 1996	UoD 2005	SEPA 2005	UoD 2006	FC 2006
nº	14,392	94	114	36	116	22
pH	0%	0%	0%	0%	0%	0%
Cl	0.22% (0.2, 0.41, 1*, 5, 8.53)	0%	0%	0%	0%	0%
SO_4	4.67% (.1**, 1, 2.9, 3.74)	0%	0%	0%	0%	0%
NO3-N	17.22% (0[!], 0.1**, 0.2, 0.3, .1**, 1)	7.45% (0.01)	2.63% (0.01)	22.22% (0.01)	0%	0%
Na	0.01% (0.14, 1)	0%	0%	0%	0%	0%
K	0.19% (.008[!],.01,.1*)	0%	7.02% (0.01*)	0%	0%	0%
Mg	0.06% (0.007[!],0.1)	0%	0%	0%	0%	0%
Ca	0.10% (0.01, 0.013, 0.03, 0.1)	0%	0%	0%	0%	0%
Alk	8.07% (0.1*, 0.3*, 0.5**, 3*, 10*, *others*)	0%	63.16% (1*)	38.89% (1*)	32.76 % (1*)	0%
DOC	0.18% (*various*)	0%	0%	0%	0%	0%

E.3 Data Screening

A three step screening process was applied to data from all data-sources

1. Outlier removal by comparison with AWMN values
2. Na:Cl ratio checks
3. Charge Balance Correction

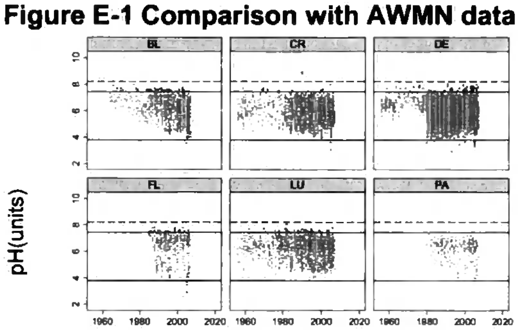
E.3.1 Comparison with the AWMN

Data for each variable were plotted by year and major catchment (Bladnoch, Cree, Fleet, Dee, Luce , Palnure) against the maximum and minimum values found across the Acid Waters Monitoring Network (Monteith and Evans, 2000; Table E-1). Rules were determined to remove clear outliers. The assumption is that the acid waters network of sites will provide a plausible distribution of likely values within which the sites for Galloway should be found. However, as the acid waters monitoring network specifically targeted acid sensitive waters and the SEPA/SRPB sampling targeted a cross-section of land-covers and geologies, each distribution was investigated individually and rules that only excluded clear outliers were generated, and values with the potential to be part of the regional trend were conserved.

Table E-1 AWMN maximum and minimum values 1988-1998 (from Monteith and Evans, 2000)

Determinant	AWMN Min	Limit Set	AWMN Max	Limit Set
pH (units)	3.97	None	7.44	8.2
Alkalinity (eq/l)	-165	None	461	1000
Ca (eq/l)	4.5	None	354.5	500
Mg (eq/l)	25	25	358.3	358.3
Na (eq/l)	69.6	69.6	813	813
K (eq/l)	2.6	None	110.3	110.3
SO4 (eq/l)	20.8	None	818	818
NO3 (eq/l)	0	None	90.7	90.7
Cl (eq/l)	50.7	None	1036.6	1036.6
DOC (mg/l)	0	None	34	50

Figure E-1 Comparison with AWMN data

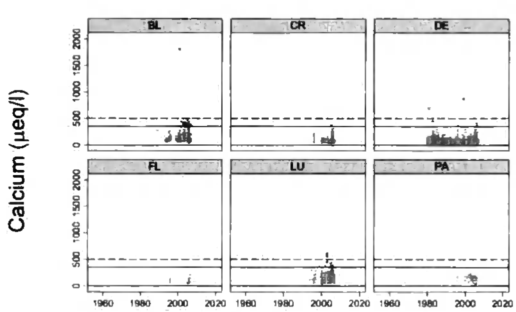


AWMN range : 3.97 < pH < 7.44
Limits used : n/a < pH < 8.20
8 records removed

Lower limit changed as includes data from surveys sampled at high flow which may have higher pH's than those at AWMN.

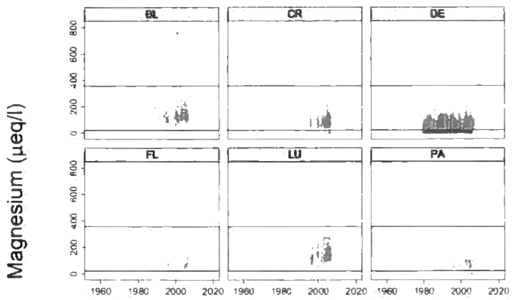
Upper limit modified to fit reasonable regional distribution

NB Dee includes weekly monitored sites, hence intensity of resolution.



AWMN range : 4.5 < pH < 354.5
Limits used : n/a < pH < 500
10 records removed

Upper limit modified to fit reasonable regional distribution, particularly in the Bladnoch.



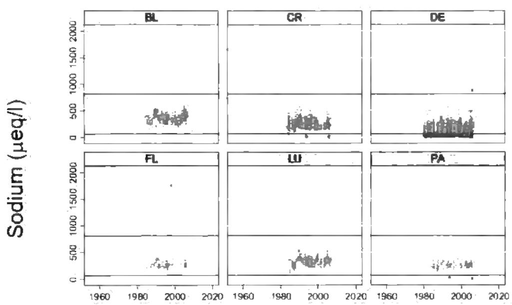
AWMN range : 25 < Mg < 358.3

Limits used : 25 < Mg < 358.3

19 records removed

AWMN range used. Only one upper limit outlier identified.

Lower limit outliers mostly in S_DE_RN which is a rainwater sample; it was left unaltered and lower limit outliers were removed from all other samples.



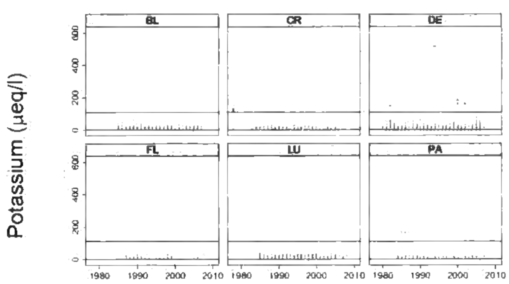
AWMN range : 69.6 < Na < 813

Limits used : 69.6 < Na < 813

10 records removed

AWMN range used. Only one upper limit outlier identified.

Lower limit outliers mostly in S_DE_RN which is a rainwater sample; it was left unaltered and lower limit outliers were removed from all other samples.



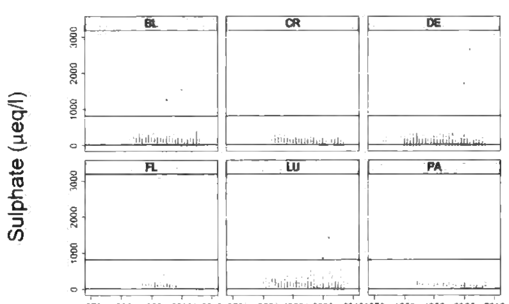
AWMN range : 2.6 < K < 110.3

Limits used : n/a < K < 110.3

10 records removed

AWMN range used.

There are additional outliers >1000μeq/l not shown on the graph for the Dee catchment



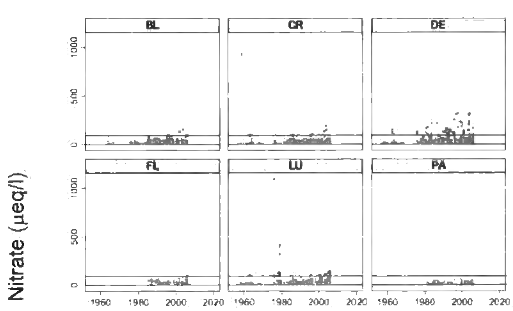
AWMN range : 20.8 < SO_4 < 818

Limits used : n/a < SO_4 < 818

7 records removed

AWMN range used.

There are additional outliers >3000 μeq/l not shown on the graph for the Dee catchment.



AWMN range : 20.8 < NO_3-N<90.7

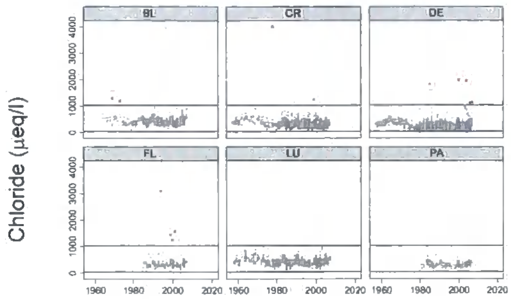
Limits used : n/a < NO_3-N< 90.7

65 records removed

AWMN range used.

Most outliers in the Dee are from rain water sample, these will be preserved.

Other outliers were checked at individual catchment scale, and found to be individual outliers from individual sites rather than from a particular site and so could be removed.

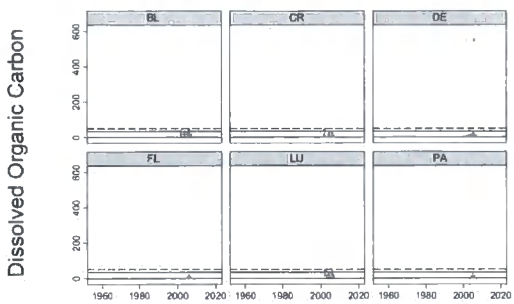


AWMN range :	50.7	< Cl <	1036.6
Limits used :	n/a	< Cl <	1036.6

15 records removed

AWMN range used.

Lower limit outliers in the Dee are from rain water sample, or part of a trend so preserved.



AWMN range :	BDL<	< DOC <	34
Limits used :	n/a	< DOC <	50

1 record removed

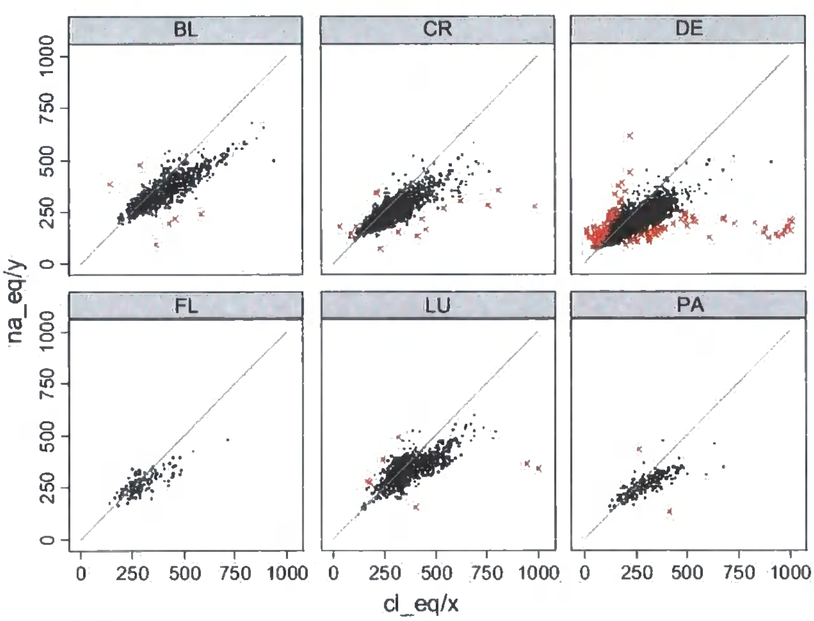
Upper limit fitted to regional distribution

DOC record begins after 2000

E.3.2 Na:Cl ratio

The majority of sodium and chloride deposited to a freshwater come from the deposition of sea salt. This is particularly true in a costal region such as Galloway. As a result the Na:Cl ratio is expected to be within a range around a 1:1 relationship. CLRTAP 2006 suggest the range 0.5 < Na/Cl < 1.5 to be suitable for identifying outliers.

Figure E-2 Identifying Na:Cl outliers



Graphs by catchment name (major catchments)

For all catchments but the Dee the distribution of outliers appeared reasonable and the highlighted records were removed as outliers (Figure E-2). Errors in the Dee system were investigated and found to be more common in the high resolution datasets used for the Loch Dee project. Further investigation showed the errors to be significantly more common in the summer and autumn months than in winter and spring (Table E-2). This suggests outliers come from periods of low rainfall where both sodium and chloride inputs are low and non-marine influences are driving sodium and chloride water chemistry. The more intensive sampling of the Loch Dee project would increase the likelihood of sampling during such a period and thus explains the proportionally high occurrence of outliers in the Dee system.

Table E-2 Distribution of Na:Cl errors by month

Month	Outliers	Month	Outliers	Month	Outliers	Month	Outliers
January	4	April	6	July	15	October	9
February	9	May	13	August	31	November	7
March	9	June	12	September	32	December	4

Following the CLRTAP (2006) methodology all Na:Cl outliers were removed (n=151) from the dataset.

E.3.3 Ionic Balance Checks

Major anions and cations play key roles in the Critical Loads model. Many studies perform (e.g. Evans et al 2003; CLRTAP 2006) use Ionic Balance checks to identify potential analytical errors. This approach assumes that with knowledge of the major cations (Equation 4) and anions (Equation 5) the majority of the ions present in the sample are known.

Equation 4: ΣBase Cations (ΣBC) = $\mathbf{Ca^{2+} + Mg^{2+} + Na^{+} + K^{+}}$

Equation 5: ΣStrong Acid Anions (ΣAA) = $\mathbf{SO4^{2-} + NO3^{2-} + Cl^{-}}$

Based on the electro-neutrality of water the sum of positive ions (cations) should be equalled by the sum of the negative ions (anions). Equation 6 (from CLRTAP, 2006) below is used to calculate the proportional charge balance, which is expected to be close to zero. A standard error threshold for charge balance errors in areas with conductivity >20µS such as Galloway is to query the validity of areas of with CB% values greater than ±10% of zero (Evans et al, 2003; CLRTAP, 2006); these cut-off lines are marked on figure E-3.

Equation 6:Charge Balance % (CB%) = $$\frac{\Sigma \text{ Base Cations} - \Sigma \text{ Acid Anions}}{\Sigma \text{ Base Cations} + \Sigma \text{ Acid Anions}} * 100$$

Figure E-3 Charge Balance error; a) histogram and b) ion distribution.

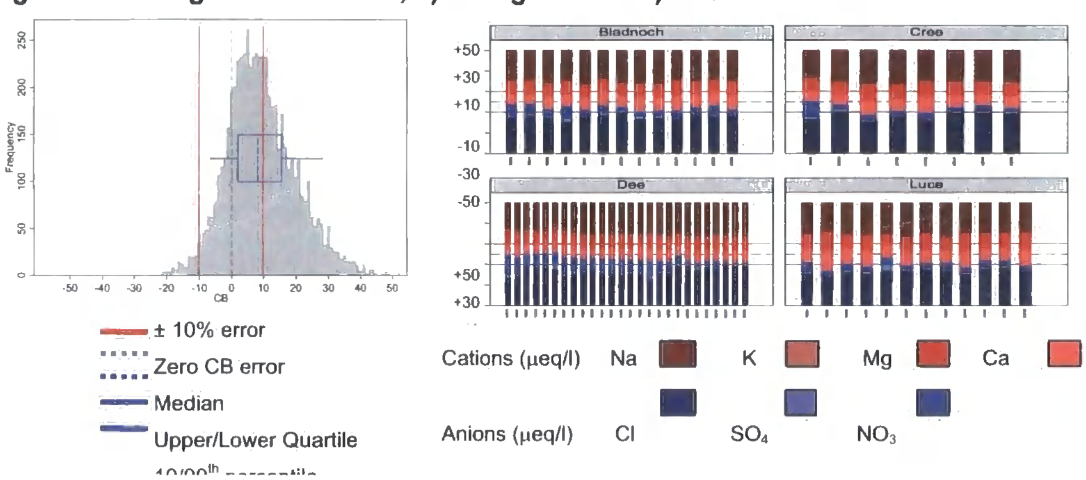
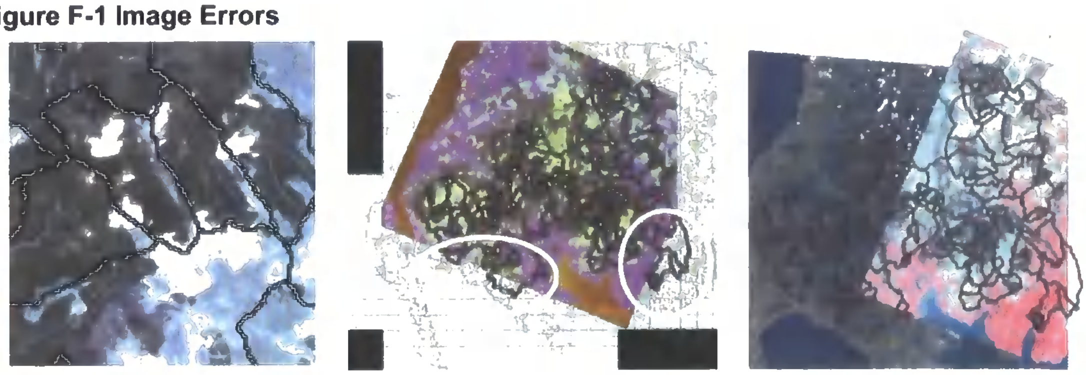


Figure E-3 above shows that the histogram of charge balance for the 5969 records for which all major anions and cations are available. The histogram and box plot show that the distribution is skewed towards positive charge balance errors; this means that recorded cations outweigh recorded anions; the ion balance diagrams show for the four larger catchments show the changes in median ion balance through time and illustrate that median chemistry is only barely within the ±10% CB limits. Median charge balance error for all sites is, in fact, +8.73 μeq/l. It is expected that this underestimate of the anion component is due to the lack of inclusion of weak acid anions from organic (humic and formic) acids. The increase in the anion underestimation over time, which is particularly notable in the Dee data, fits well with expected trends of increased DOC and organic acid contributions noted by other authors (e.g. Evans et al, 2007, Worrall 2007). Work has shown that it is possible to estimate the contribution of these ions with a knowledge of DOC and pH (Oliver et al, 1983; Driscol et al, 1994) however insufficient DOC information is available to perform this correction. An exploration using the equations of Driscoll (1994) and Oliver (1983) for the sites for which DOC data are available estimates the contribution of organic acid anions to be large with a median contribution of 66μeq/l (Driscoll) and 73μeq/l (Oliver). These values significantly over correct the ion balance equation, and so require suggest the need for significant further investigation and potentially creation of a Galloway DOC/pH based model to accurately understand the contribution to overall acidity played by organic carbons.

As excluding charge balance errors outside of the ±10% range would have lead to a loss of 46% of the available data (2732 records) it was decided instead to tag charge balance errors for further reference and retain all the data within the dataset.

Appendix F Imagery Constraints

Figure F-1 Image Errors



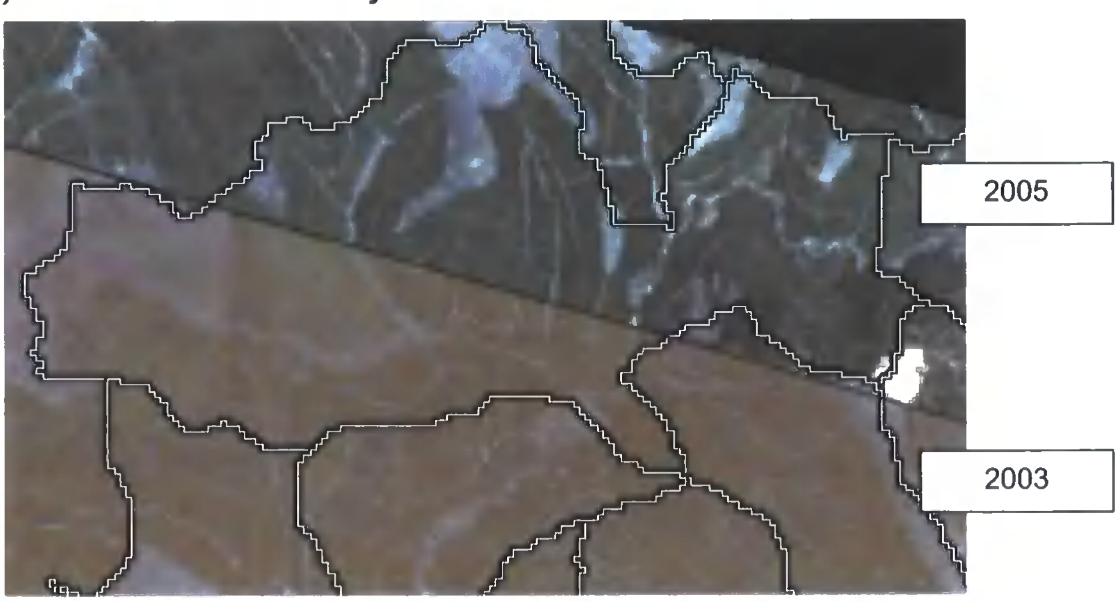
i) Cloud cover   ii) image extent   iii) 2003: both i) and ii)

As Figure F-1 demonstrates there were three issues of image quality for which image corrections were applied. These were: i) corrections for cloud cover ii) corrections for when catchments fell outside of the extent of the radiometrically corrected image and iii) issues in 2003 when two images were combined.

i) Cloud cover.

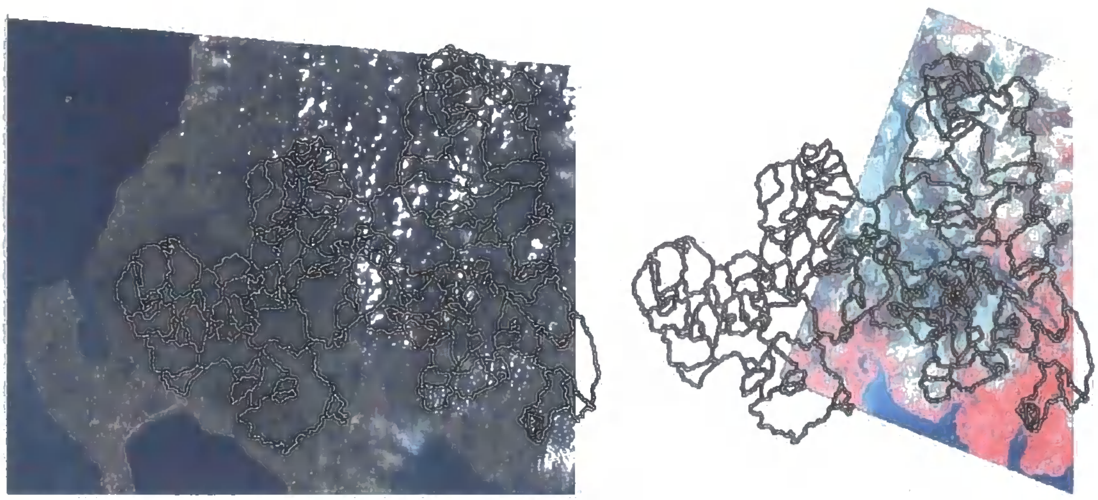
Cloud cover obscured catchments in the 2001 and 2003 Landsat images. Each impacted was identified and the erroneous canopy closure data were replaced by those of another year. As only very small areas of land (0.93km^2; 0.04%) needed to be corrected in this way, and the replacements were only from data 2 years separate (2001 data replaced with 2003 data; 2003 data replaced by 2005 data) these changes are not seen to be likely to cause a significant influence on results.

ii) Outside of radiometrically corrected extent.



Areas outside of the extent of the imagery were identified on non-radiometrically corrected images and revealed to contain only very small proportions of forestry. These were added back in by digitising their total area and divided between forestry proportions using the known ratio between 2-8m forest and > 8m forest from a nearby forest compartment. This assumes that the areas have similar planting ages to the area used to provide the forest proportions, however such small percentages of the total area (>0.001%) were involved that any errors introduced are likely to be insignificant.

iii) 2003 data cloud and extent.



In 2003 two complementary images were available, i) a Landsat Image with significant cloud cover in the eastern half of the image, and ii) a SPOT image covering only the eastern extent. The two images were combined to minimise these issues contained within the individual images.

Appendix G Minutes of stakeholder meeting

Report: Forestry, Critical Loads & Policy Meeting, 31st Aug 2006, SEPA Newton Stewart.

A3 Meeting Document.

A pdf version of the data presented at the meeting updated with the above corrections accompanies these notes. The GFT have requested that this information is to be used solely in the context of this project and that any external use should not take place without prior consultation with them.

Meeting Attendees:

Galloway Fisheries Trust: GFT senior fisheries scientist (GFT), Additional GFT representatives (GFT-2, GFT-S2)

Forestry Commission: FCC (FC conservator), Forestry Commission Hydrologist (FCH), Galloway Forest District Manager (FC-G), FC1

University of Durham: Rob Dunford (RWD).

Scottish Environmental Protection Agency: Local SEPA representatives SEPA-1, SEPA-2, SEPA Ecologist (SEPA-Ec), Head of SEPA Newton Stewart (SEPA-NS),

Summary of Key Points

1. SEPA's Classification of Water Bodies

i. SEPA confirmed fish data were not used to classify the rivers at risk of acidification, and that the most vulnerable indicator species was used (Invertebrates or diatoms).

ii. FCH raised possibility that data suggests we are seeing a return to pre-deposition chemical conditions.

iii. FCH suggested that there was a need to look into possibility that natural acidity (non-forest exacerbated acidity) is now dominating water chemistry.

iv. FCH suggested SEPA classification system should take this into account.

v. FCH suggested SEPA might investigate a more robust classification methodology based on Critical Loads.

vi. SEPA-Ec agreed that SEPA and FC would need to work more closely regarding these issues.

2. Catchment Forestry and the 300m rule.

i. Very few catchments identified by SEPA as at risk of acidification due to forestry were over 300m

ii. Issues concerning the utility of the altitude-based rule were raised.

iii. Questions regarding the science behind the 300m limit were raised and FCH confirmed that the evidence base drew on cloud base data from regional airport.

iv. It was queried whether this approach was relevant to Galloway where the cloud level was often below 300m.

v. The GFT asked if areas below 300m (such as the Fleet) would be considered if significant impacts were highlighted.

vi. FCH explained that the F&WGs provide guidance rather than set rules, and that flexibility is expected, tailored to local conditions.

vii. FCC agreed that Critical Loads testing would be considered in areas below 300m where justified by local concerns.

3. Critical Loads Scenarios (ANC)

i. It was clear to all that there was not a significant match between the exceeded catchments derived from the Critical Loads model and the at risk catchments identified by SEPA's initial water body classification for the WFD.

ii. FCH stressed that using an ANC of 0 for the F&WGs was already taking a cautionary approach because high flow samples were targeted, and that ANC 0 at high flow was probably equivalent to a minimum of ANC 20 at mean flow.

iii. Increasing the high flow ANC to 20 significantly increased the number of exceeded catchments in some scenarios (in some cases by more than double).

iv. GFT raised concern that GFT/SEPA data showed a large acidification impact in many catchments (e.g. Upper Dee, Cree) but CL's were not exceeded, suggesting that replanting posed no risk.

v. GFT raised particular concern for the Upper Bladnoch as it is an SAC and aquatic biodiversity appears heavily impacted by acidification, however the F&WGs indicate that the waters are protected from further acidification due to forest replanting.

vi. FCC stressed that Forest Plans were regularly reviewed and focused on the next 5 years of work; further opportunities for consultation would follow and take account of changes in science and legislation.

vii. FCH again raised the points in sections 1ii-vi suggesting that we were seeing evidence of chemical and some biological recovery but there was a need to consider limits on recovery imposed by natural acidity.

viii. Queries were raised regarding the relevance of the ANC thresholds derived from Scandinavian data to Galloway rivers.

ix. FCH and GFT agreed to work together to see if ANC-fish response curves could be determined for Galloway.

x. GFT stressed the need to allow for uncertainty in the Critical Loads estimates, especially when considering catchments that marginally pass or fail. FCH said that the guidelines allowed for marginal sites to be resampled for checking and that this was guided by local discussions.

xi. FCH stressed the need to organise a meeting to consider how the data from the Loch Dee Project could help to validate and refine the Critical Loads approach.

4. Fisheries Perspective.

i. There was a need for improved knowledge of barriers to fish movement in Galloway rivers.

ii. FDM expressed an opinion that egg box experiments were persuasive. GFT stressed that experience showed them to be a relatively blunt tool.

iii. FDM requested a map of areas where GFT/SEPA think recovery is underway in order to target these for management actions.

5. Combined Datasets

i. All agreed that there was a need to review existing monitoring work and try to adjust programmes so that the same reaches of river were targeted for water chemistry, invertebrate and fishery assessments in order to maximise data value. A meeting will be organised to try and arrange this.

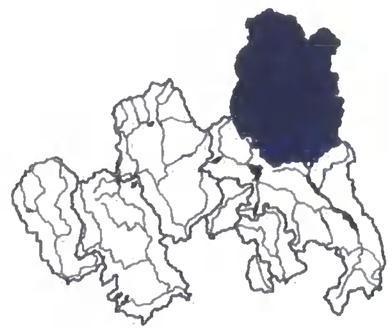
Appendix H Regional pH through time (1955-2006)

The following graphs map the changes in pH through time as reported in the SRPB reports and shown in the long-term SEPA database. The data of Wright *et al.* (1979), Puhr (1997) and this thesis (2005/2006) is also shown. The entire catchment relies on a single sample leading to the potential for sub-basins to be misrepresented.

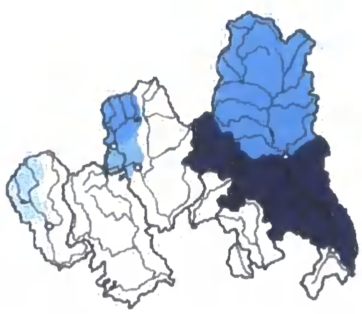
Legend

- 0.1 - 3.0
- 3.1 - 4.0
- 4.1 - 4.2
- 4.3 - 4.4
- 4.5 - 4.6
- 4.7 - 4.6
- 4.7 - 4.8
- 4.9 - 5.0
- 5.1 - 5.2
- 5.3 - 5.4
- 5.5 - 5.6
- 5.7 - 5.8
- 5.9 - 6.0
- 6.1 - 1000.0

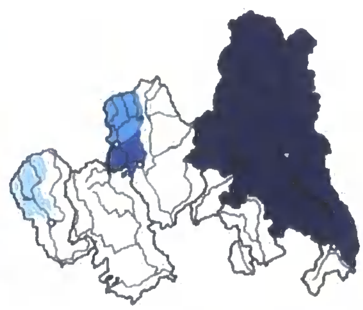
1955



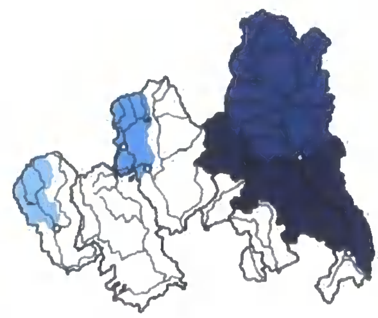
1956



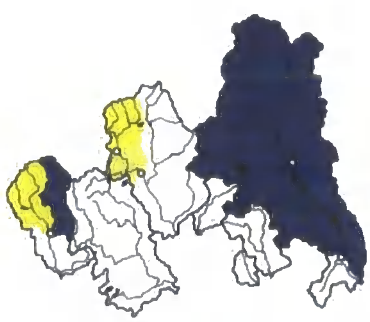
1957



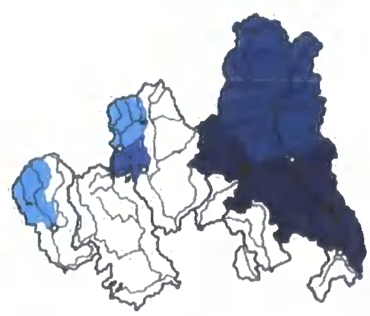
1958



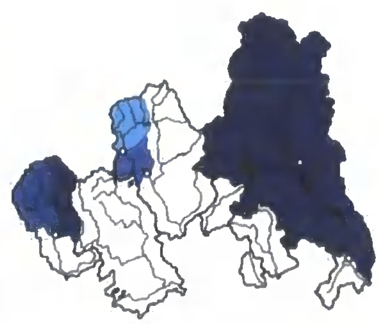
1959



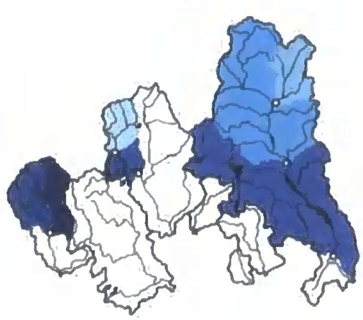
1960



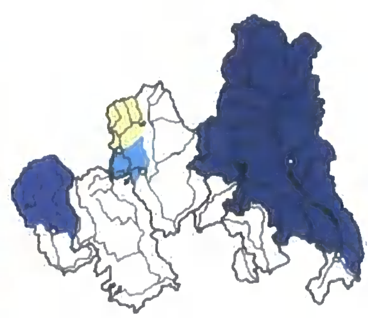
1961



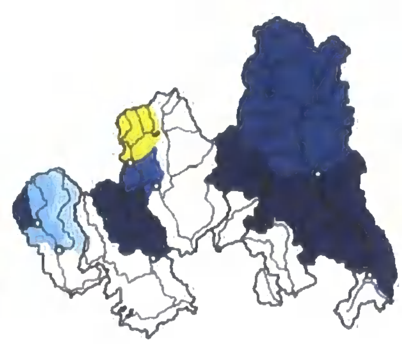
1962

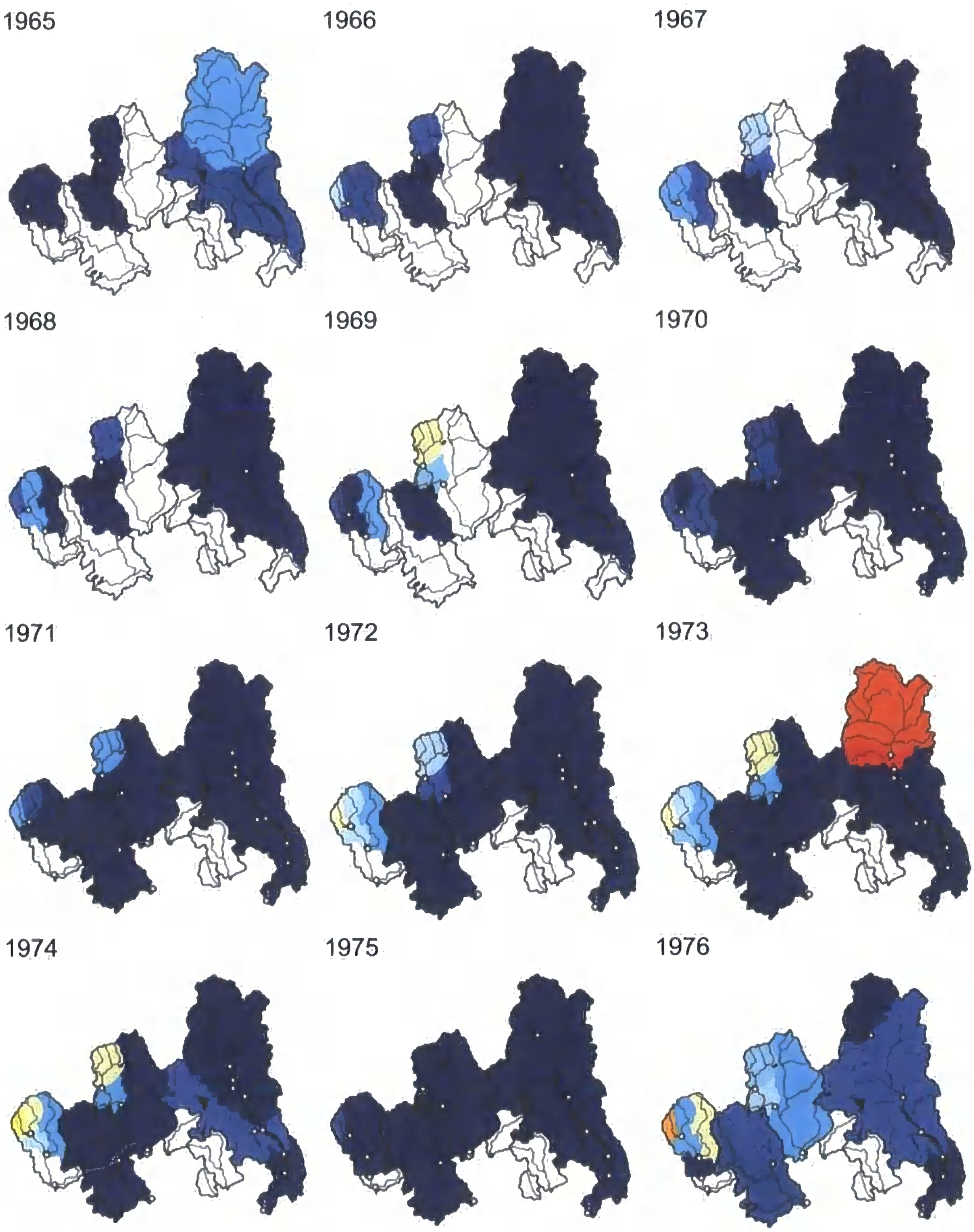


1963



1964




1965
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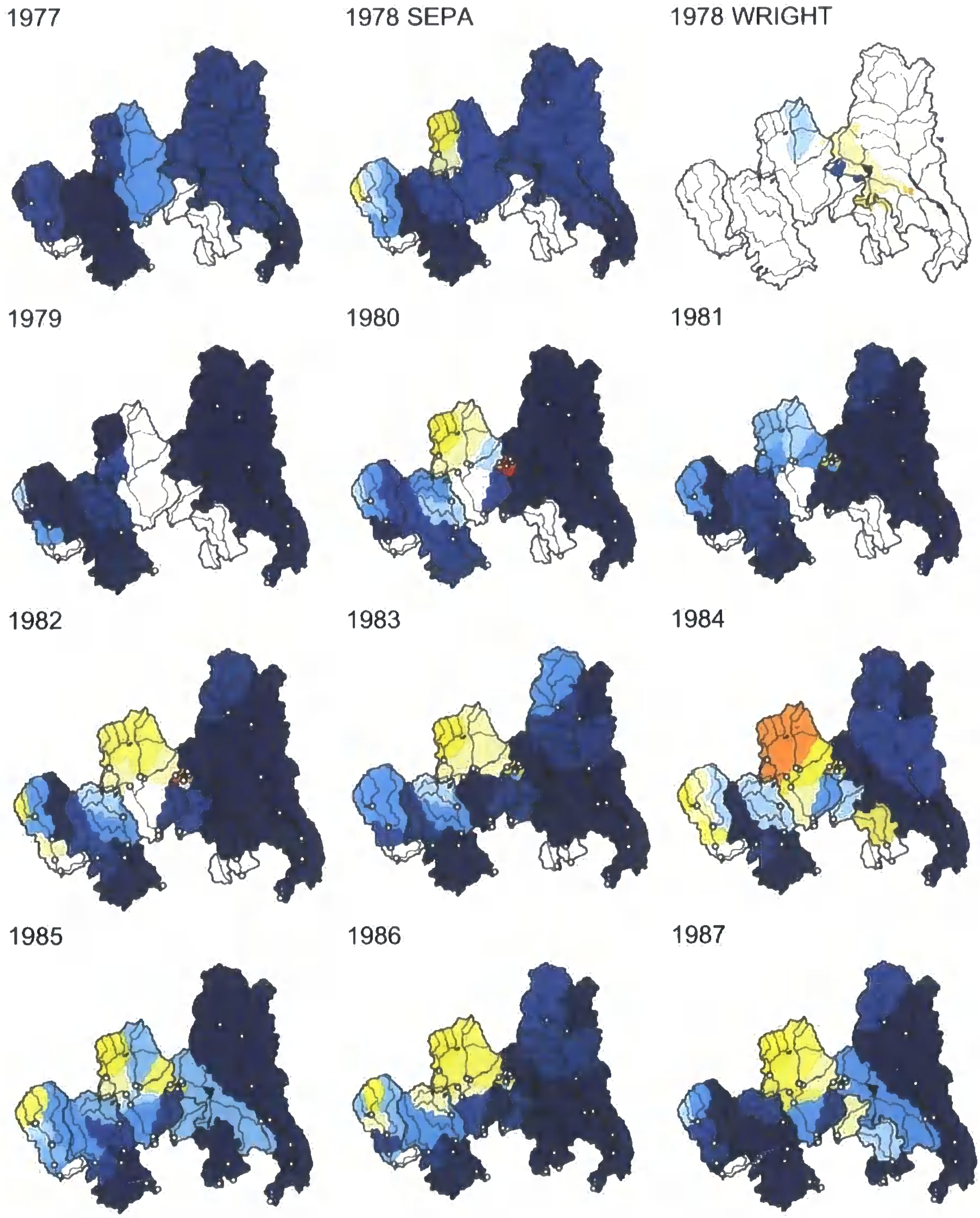
1976


1977
1978 SEPA
1978 WRIGHT
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1980
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1982
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1984
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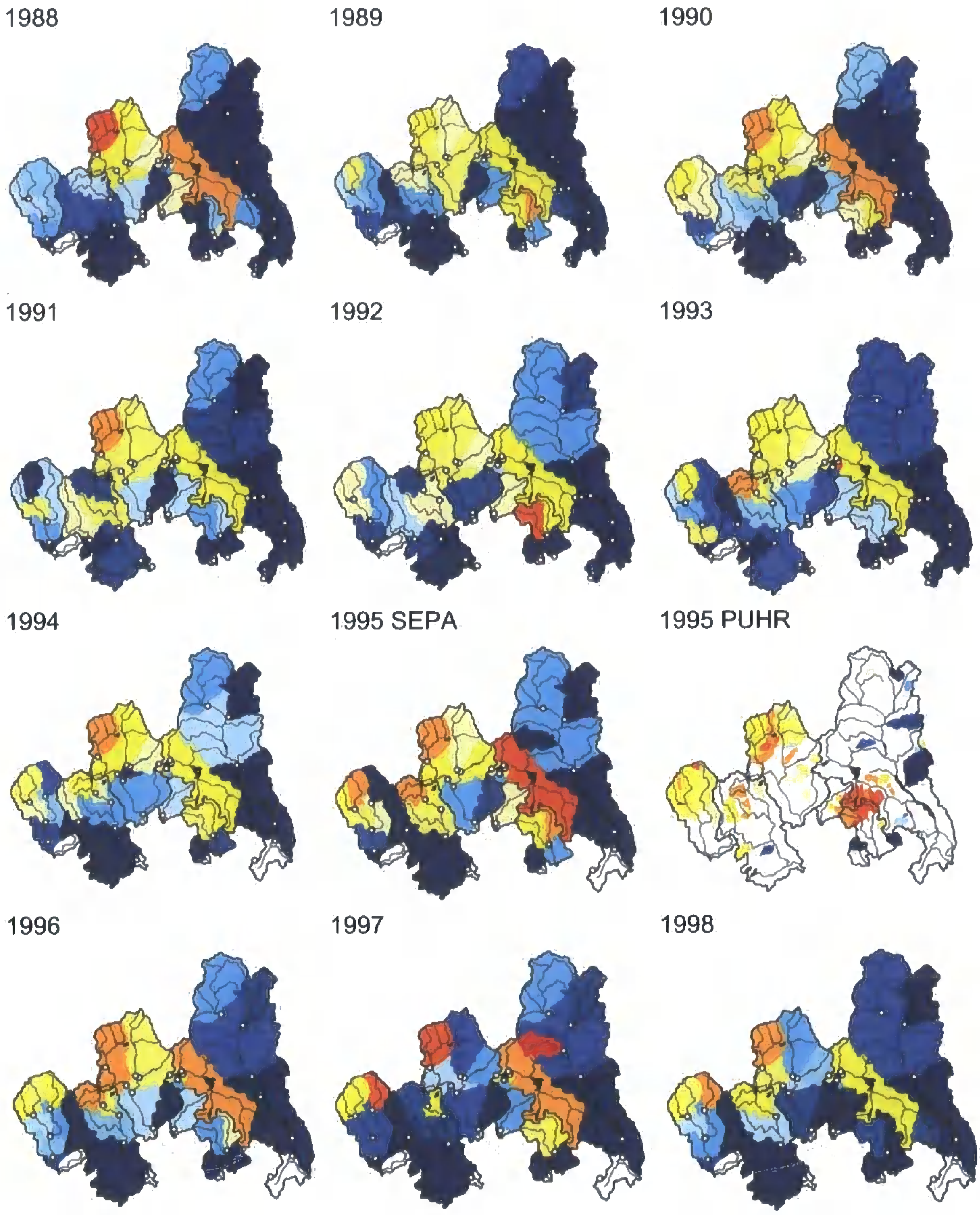
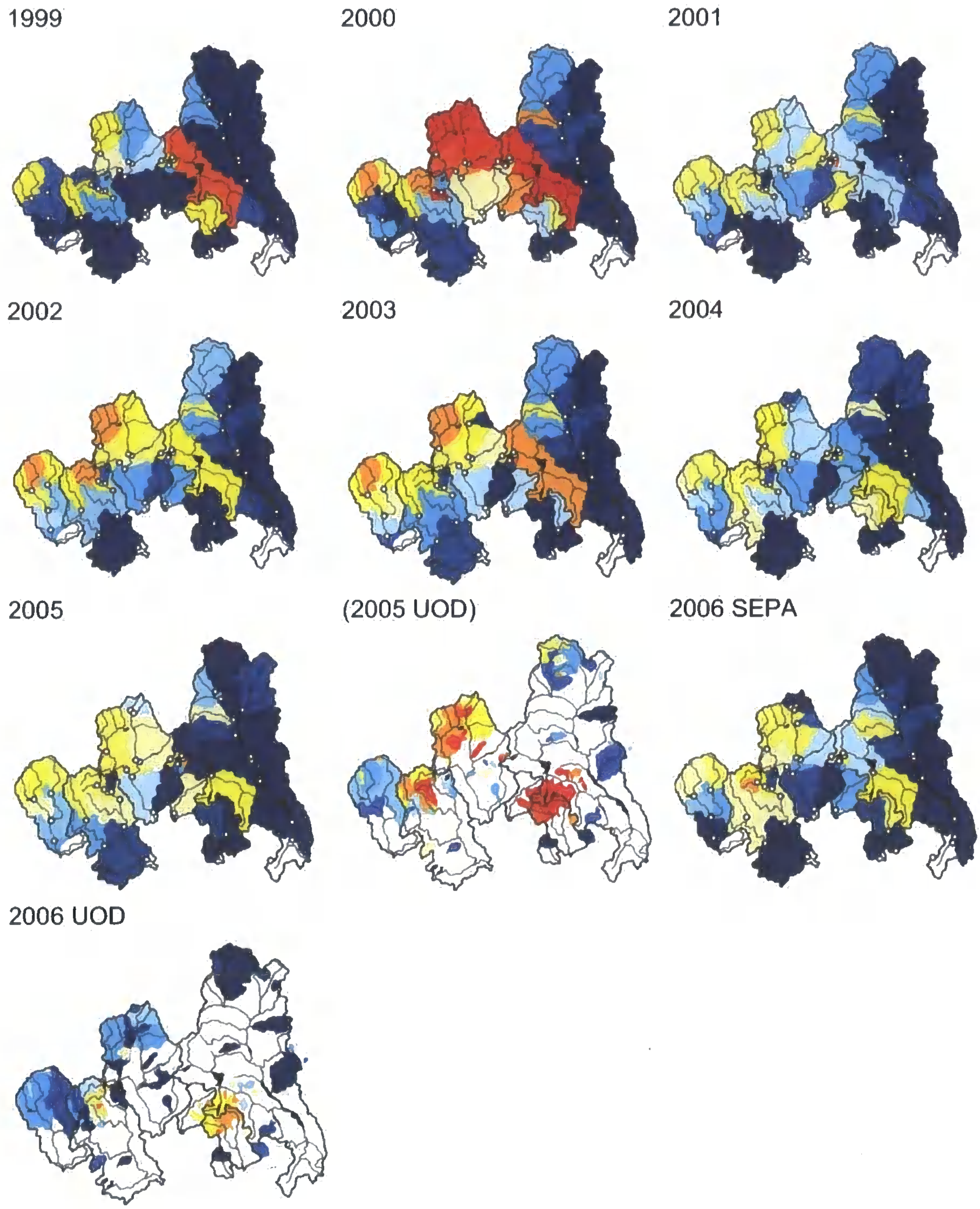
1986
1987


1988
1989
1990
1991
1992
1993
1994
1995 SEPA
1995 PUHR
1996
1997
1998


1999
2000
2001
2002
2003
2004
2005
(2005 UOD)
2006 SEPA
2006 UOD

Appendix I Primary Data CD

The CD attached to this thesis contains the following files:

- All_PhD-Data_Stata.dta
    - Contains all Chemistry Data processed within this thesis (Stata Format)
- *_Interview.doc
    - 6 x Document files of transcribed interviews (MS word format)
- Stakeholder_Meeting_SummaryQuotes.doc
    - Summary quotes from the stakeholder meeting (MS word format).